doi: 10.25750/1995-4301-2022-3-058-067

NDVI – alpha diversity relationship in tropical montane cloud forest of Ecuador

© 2022. S. Llerena[1, 2] ORCID: 0000-0002-0491-530X,
G. Toasa[3] ORCID: 0000-0002-3739-2613,
A. I. Kurbatova[1] ORCID: 0000-0002-7763-5034,
[1]Peoples' Friendship University of Russia,
6, Miklukho-Maklaya St., Moscow, Russia, 117198,
[2] Amazon Regional University Ikiam,
8 km road to Muyuna, Tena, Ecuador, 150150,
[3]Independent Biologist-Botanist,
Av. General Rumiñahui, Quito, Ecuador, 170501,
e-mail: alellerenag@gmail.com

In tropical forest the biodiversity is in a constant threat, some species are listed in the IUCN as vulnerable, endangered or threatened with extinction. Thus, a fast method for biodiversity determination or monitoring can contribute to its conservation. Remote sensing has demonstrated to be a powerful tool, and together with the vegetation indexes, can determine the vegetation state of forest. Recently researches have correlated the normalized differentiated vegetation index (NDVI) with species richness, structure and biodiversity of forests obtaining successful results.

This study, conducted in a Tropical Montane Cloud Forest (TMCF) of Ecuador, aims to correlate NDVI with alpha diversity estimators to understand its relationships. NDVI of Landsat OLI 8 Level 1 images in five months was determined. We considered a scene as valid in case of cloud coverage in the areas of interest below 25%. Radiometric and atmospheric corrections, with flaash tool, and the delimitation of the study site (ROI) were developed in ENVI 5.3 program. NDVI was calculated with ENVI 5.3 program (histograms allowed the determination of mean, maximum and minimum NDVI), and with ArcGIS 10.3 (for classification index). In field, species richness, Chao1, Shannon index, Simpson index, and biomass of three plots were quantified for trees with DBH ≥ 10 cm. Then, we calculate Pearson coefficient to correlate and disentangle the effects of altitude, diversity, richness, biomass and NDVI. A positive relationship was observed between Mean NDVI and Chao1 ($p < 0.10$) and Mean NDVI – richness ($p < 0.05$). In conclusion, NDVI can be considered useful to estimate richness and biodiversity and even to detect ecotone as was the case in this research. The application of this methodology could allow biodiversity assessment and monitoring in real time and low cost, which contributes in forest conservation programs.

Keywords: Landsat, normalized differentiated vegetation index, vegetation richness, diversity, tropical montane cloud forest.

УДК 504.064.37;502.2.05

Соотношение NDVI и альфа-разнообразия в тропических влажных горных лесах Эквадора

© 2022. С. Йерена[1, 2], инженер, аспирант,
Г. Тоаса[3], биолог, ботаник, А. И. Курбатова[1], к. б. н., доцент,
[1]Российский университет дружбы народов,
117198, Россия, г. Москва, ул. Миклухо-Маклая, д. 6,
[2]Региональный университет Амазонки Икиам,
150150, Эквадор, г. Тена, 8 км дороги в Муюну,
[3]Независимый исследователь,
170501, Эквадор, г. Кито, просп. Генерала Руминьяуи,
e-mail: alellerenag@gmail.com

За прошедшее десятилетие на международном уровне значительно усилилась озабоченность проблемой обезлесения и её воздействия на усиление климатических изменений, утраты биоразнообразия и предоставление экосистемных услуг. Биоразнообразие является важным фактором устойчивости лесных экосистем, их способности

давать отклик на внешнее воздействие. Исследование биоразнообразия методами дистанционного зондирования Земли как основы устойчивого развития экосистемы тропического леса является актуальной задачей.

В недавних работах была выявлена положительная корреляция нормализованного дифференцированного индекса растительности (NDVI) с видовым разнообразием тропических лесов. Данное исследование тропического горного туманного леса Эквадора направлено на сопоставление NDVI с оценками альфа-разнообразия для определения характера их взаимосвязи. В работе по спутниковым снимкам Landsat OLI 8 уровня обработки Level 1 был определён NDVI за пять месяцев. В полевых условиях видовое разнообразие, индекс Chao1, индекс Шеннона, индекс Симпсона и биомасса на трёх участках были количественно определены для деревьев с диаметром ствола ≥ 10 см. Далее для выявления взаимосвязи эффектов высоты, качественных и количественных показателей разнообразия с NDVI был рассчитан коэффициент Пирсона и определена взаимосвязь между средним значением NDVI и индексом Chao1 ($p < 0{,}10$), а также между средним значением NDVI и видовым богатством ($p < 0{,}05$). Применение этой методологии может позволить проводить оценку и мониторинг биоразнообразия в режиме реального времени и с низкими затратами, что способствует реализации программ по сохранению лесов.

Ключевые слова: Landsat, нормализованный дифференцированный индекс растительности, разнообразие растительного покрова, биоразнообразие, тропический влажный горный лес.

The Andes Mountain range is along the center of Ecuador and includes Tropical Montane Cloud Forest (TMCF). It is considered a hotspot due to their biological richness and high level of endemism. Agriculture expansion plus extensive cattle ranching and forest clearing have fragmented and isolated this ecosystem. For this reason, the tropical Andes are a world conservation priority [1–3].

The knowledge of richness species and biodiversity in these forests is necessary to develop monitoring and conservation strategies. Owing to its current state of critical conservation, the tropical forest needs a rapid method for assessment and monitoring the biodiversity. For this type of forests, with high levels of biodiversity, the traditional field methodology is often costly and time consuming [4, 5]. Remote sensing has displayed great potential to perform this labor. This is a fast and nondestructive method which allows to estimate species richness, biodiversity and characterize the structure and composition of forests [6–8].

Thanks to satellites, it is possible to acquire, process and interpret images of a distant objects. Landsat 8 satellite was launched in 2013, its images are processed by geographic information systems (GIS), and have been used to assess the state of tropical forests and quantify properties of the earth's surface at a high spatial and spectral resolution with the application of vegetation indexes [5, 9, 10]. Normalized Difference Vegetation Index (NDVI) is one of the most used vegetation index, it was introduced by Rouse et al. in 1974 and takes advantage of the fact that greener or healthier vegetation absorbs more visible light and reflects a large amount of near infrared light, while unhealthy or sparse vegetation (less green) reflects a large portion of visible light and less near infrared light [11]. Chlorophyll pigments, which are the largest absorbers of radiation in the visible region, absorb in the red and blue regions of the visible spectrum (wavelength bands between 0.44 and 0.66 μm), but not in the green region where the reflectivity is much higher and its maximum value is observed in the near infrared range [12].

NDVI is found in many studies related with forest assessments or monitoring studies. It has been used to predict species richness [4, 13–17]. Also, it is associated with forest structure [5, 18–20]. With the contribution of the species-energy theory, NDVI has been connected with patterns of species diversity and tree species composition [4, 7, 21]. This theory states the energy as a limiting resource for species in an specific area [22].Thus, the greater resource availability increase the primary productivity, specialization and diversity of species [5]. In addition, biodiversity and richness researches have shown a positive correlation between NDVI and diversity indexes like Shannon and Simpson [4, 23–27].

Although the number of investigations about biodiversity and its relationship with NDVI has increased, there are no studies that use this index and correlates it with species richness or biodiversity in tropical montane cloud forest (TMCF). Therefore, our aim is to demonstrate the potential of using remote sensing through NDVI to determine diversity and species richness in "El Cedral Ecolodge" a TMCF. The results will help to monitor the biodiversity in this type of forest and can be applied in other forests.

Materials and Methods

The study area is El Cedral Ecolodge with extension of 71 ha. It belongs to TCMF within Eastern Cordillera Real montane forests (NT0121). It is located in Yunguilla in the Northwestern of Pichincha province (Fig. 1),

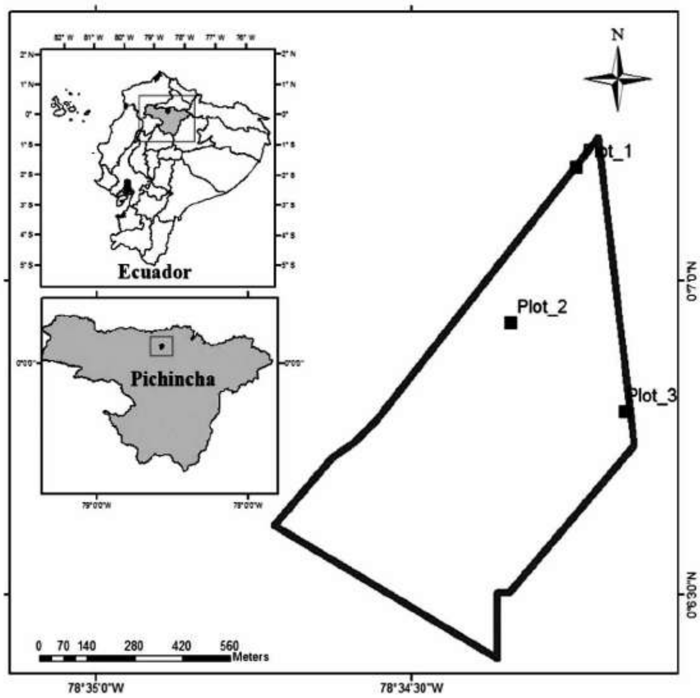

Fig. 1. Distribution map of the plots in the study area

in Ecuador country (latitude 0.114055° and longitude -78.570176°). The topography is rugged with sloping ravines and few flat areas. The annual precipitation ranges are between 1394 to 2414 mm. The vegetation cover is continuous with a canopy between 20 and 25 meters high. The site experiences two rainy seasons: March – April and October – November. According with the methodology of the National Forest Assessment of Ecuador [28], three plots of 60 m × 60 m were established (plot 1: 2521 meters above sea level (m.a.s.l.), plot 2: 2409 m.a.s.l., and plot 3: 2220 m.a.s.l.).

In each plot of 60 m × 60 m, all individuals with a Diameter at Breast Height (DBH) ≥ 10 cm were sampled. The DBH ≥ 10 cm was measured at 1.3 meters [29]. The species identification was carried out based on botanical samples collected previously [30], virtual herbarium specimens, specialized literature of similar vegetation to the study area. Later, scientific names and distributions of the species were verified with the Catalog of Vascular Plants of Ecuador [31], and the database from Tropicos website [32]. Finally, a database with taxonomic information (S1) associated to each specimen was created and transformed to compatibles files with statistical packages PAST 2.17c [33], and JMP v 8.0 [34] where alpha species diversity estimators (richness S, Chao1, Shannon and Simpson indexes) were quantified.

For richness (S) calculation, the total number of species in each plot was registered [35]. Also, the richness estimator Chao1, based on the rare species number, was determined with the following formula [36]:

$$\text{Chao1} = S + \frac{a^2}{2b}$$

In the formula S is the species number in a sample, a is the number of singletons and b is the number of doubletons [37]. In addition, Shannon index (H) [38, 39] was calculated with the following formula:

$$H = -\sum_{i=1}^{S} p_i \cdot \ln p_i,$$

where S is the species number, p_i the total sample proportion corresponding to the specie i in a plot, and ln is natural logarithm. We considered low diversity $H = 0 - 0.35$, medium diversity $H = 0{,}36 - 0.7$, and high diversity $H = 0.71 - 1$.

Also, Simpson index ($D1$) was determined by the following formula:

$$D1 = 1 - \sum_{i=1}^{S} p_i^2.$$

The variables represent the same as in Shannon index. The interval of $D1$ is between 0 and 1, $D1$ = 0 means one species.

The above ground biomass (AGB) of each individual of each plot was estimated based on the allometric equation for humid montane forests [40]. In this equation, D represents the diameter (cm) and *Dens* is the wood density (g/cm^3). In order to get density values, a bibliographic review for each species was carried out and an average value was assigned [41]. The AGB formula is:

$$AGB = \exp[3.44153 + (-1.80919 \cdot \ln D) + \\ + (1.23665 \cdot (\ln D)^2) + (-0.12606 \cdot (\ln D)^3) + \\ + 1.7438 \cdot \ln(Dens)]$$

Five Landsat OLI 8 Level 1 images were downloaded from the United States Geological Surveys (USGS), for March, August, September, October and December. Thus, an annual variation in the vegetation index could be determined. A valid Landsat image had as a requirement the percentage of cloud coverage less than 25 in the area of interest. Landsat image processing was developed in ENVI 5.3 program. Here, the area of interest (ROI) was specified in the multispectral file (MTL). Radiometric calibration and atmospheric correction, with FLAASH Atmospheric Correction Model of the program, were performed. From these images, the NDVI was calculated with the formula:

$$NDVI = \frac{NIR - RED}{NIR + RED}.$$

where NIR is near infrared region (wavelength bands between 0.75–1.3 μm) and RED is red region (wavelength bands between 0.62–0.75 μm) of visible spectrum [12]. The relations between the coefficients in the formula generates values in the range of – 1 and +1 (Table 1), where the intervals represent different types of land cover [42–44].

Finally, the quick statistics (mean, maximum, minimum and StdDev) from histograms were extracted for each NDVI image, and the corresponding NDVI values for pixels of the three plots were extracted from each image.

Then, Mean NDVI of all pixels falling in each plot (60 m × 60 m) at different elevation gradient and in each month was determined. These results were correlated with elevation, diversity indexes (Shannon Wiener, Simpson), richness (*S* and Chao1), and biomass for each plot in STATISTICA program. Finally, for the most significant correlations, simple linear regressions were developed in RStudio software [45]. The strength of relationship was assessed by using coefficient of determination (r^2) and p value.

Results

A total of 657 individuals with a DBH ≥ 10 cm were registered in 3 plots (1.08 ha). In plot 1, the total individuals were 239 and 40 species were found. Plot 2 obtained a total of 247 individuals and 45 species. Finally, the total individuals in plot 3 was 171 with 43 species. Thus, the density of individuals in plot 3 was the lowest. When considering the altitudinal gradient, it was found that plot 2, located a 2409 m.a.s.l., possess the greatest species richness (S = 45, Chao1 = 51), followed by plot 3 (2220 m.a.s.l.) with 43 species (Chao1 = 49.6) and plot 1 (2521 m.a.s.l.) with 40 species (Chao1 = 44.5). These data could define plot 2 as an ecotone between this 300-meter gradient, if we consider that diversity (Shannon and Simpson indexes) decreases with altitude (Table 2).

Table 1

Intervals of NDVI scale

NDVI values	Type of land cover
< 0	No vegetation, water, clouds
0–0.09	Bare ground (degraded land, settlements, soil without vegetation cover)
0.1–0.29	Sparse Vegetation (scattered shrub, irrigated crops)
0.3–0.49	Medium Vegetation (forest plantations, bushes, slow-growing plantations)
> 0.5	Dense Vegetation (forest, dense growth plants)

Table 2

Richness and Diversity indexes for 3 plots in "El Cedral"

Richness and Diversity indexes	Plot 1 (2521 m.a.s.l.)	Plot 2 (2409 m.a.s.l.)	Plot 3 (2220 m.a.s.l.)
Shannon Wiener	3.15	3.105	3.38
Simpson	0.93	0.91	0.95
Chao 1	44.5	51	49.6
Richness (S)	40	45	43

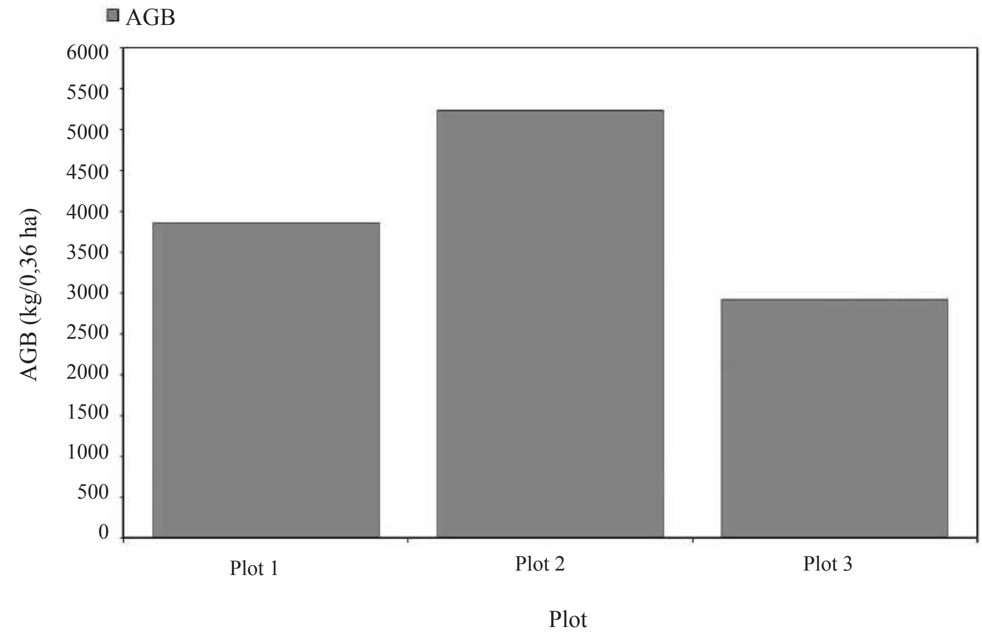

Fig. 2. Aboveground biomass (AGB) in kg/0.36 ha for three plots in "El Cedral"

The calculated biomass was 3858.41 kg/0.36 ha (Mean 16.14, Sd 7.77) in plot 1, 5230.48 kg/0.36 ha (Mean 21.17, Sd 10.74) in plot 2 and 2926.58 kg/0.36ha (Mean 17.11, Sd 8.48) in plot 3. Like in richness species, plot 2 showed the greatest value of biomass (Fig. 2).

Mean NDVI differences, for each plot, between rainy season (March, August, September, and October) and dry season (December) are clear (Fig. 3, see color insert IV). All NDVI for each plot in rainy season is more than 0.5 (Dense vegetation), while mean NDVI in December is located in the interval 0.3–0.49 (Medium vegetation). Accordingly, NDVI value decreases between rainy and dry season.

In the monthly NDVI data (Table 3) the same result of the NDVI graphs can be observed. In the rainy season, the months of March, August, September and October shows a mean NDVI of 0.82, 0.92, 0.86 and 0.79 respectively, that corresponds to dense vegetation. On the other hand, on December (dry season month) the media NDVI for the tree plots is 0.47 (medium vegetation).

In the relationships NDVI-richness and NDVI-biodiversity at different altitudes and seasons, it was found that in rainy season the NDVI correlates with Chao1 index with a positive Pearson coefficient (March: r = 0.992, August: r = 0.983, September: r = 0.963, October: r = 0.7) with a significance between 0.07 and 0.1. With richness (S) the relationship with NDVI was also positive, however the level of significance was lower than the previous mentioned. This could be mainly due to the small number of plots sampled. A strong and significant correlation was found between mean NDVI and elevation in October (Fig. 4, r = -0.99, p < 0.06). In remain months, a negative correlation was also obtained, but the significance was lower, due to the number of plots.

Discussion

The alpha diversity indexes yielded high diversity results for TMCF. Similar results have been seen in Ecuador, such as those found in the study carried out in Andean Montane Evergreen Forest at an altitude of 2705 m.a.s.l. Here, diversity was high with a maximum index of Shannon species of 0.90 and Simpson of 0.87. In general, in this type of tropical forest at altitudes between 2000 and 3000 m.a.s.l., similar diversity values are observed, as is the case of Peruvian Andean Montane Cloud Forest were diversity indexes reached higher values. Simpson index was located between 0.8 and 0.19 and Shannon index between 2.7 and 3.6 [46]. Likewise, in Myanmar Tropical Forest the maximum Shannon Diversity Index was 3.20 and Simpson Diversity Index 0.96. This study pointed precipitation as crucial factor in the development of plant diversity [47].

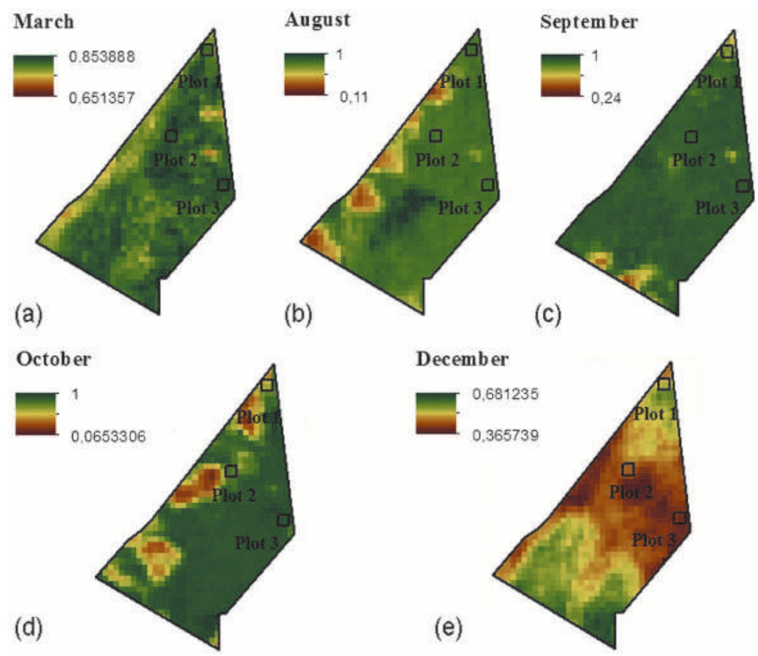

Fig. 3. "El Cedral" Normalized Differential Vegetation Index map for: (a) March 2019, (b) August 2019, (c) September 2019, (d) October 2019, (e) December 2019

Table 3

Minimum, maximum, and mean NDVI ± standard deviation of NDVI by months

Plot	Min NDVI	Max NDVI	Mean NDVI	StdDev
March				
Plot 1	0.80	0.83	0.81	0.01
Plot 2	0.82	0.84	0.83	0.01
Plot 3	0.82	0.83	0.83	0.00
NDVI Mean (month)	0.81	0.83	0.82	0.01
August				
Plot 1	0.86	0.93	0.89	0.02
Plot 2	0.90	0.96	0.93	0.02
Plot 3	0.90	0.95	0.93	0.02
NDVI Mean (month)	0.89	0.95	0.92	0.02
September				
Plot 1	0.69	0.85	0.79	0.05
Plot 2	0.88	0.91	0.89	0.01
Plot 3	0.87	0.93	0.90	0.02
NDVI Mean (month)	0.81	0.90	0.86	0.03
October				
Plot 1	0.45	0.85	0.70	0.13
Plot 2	0.70	0.84	0.79	0.25
Plot 3	0.82	0.93	0.89	0.03
NDVI Mean (month)	0.66	0.87	0.79	0.14
December				
Plot 1	0.51	0.58	0.54	0.03
Plot 2	0.44	0.47	0.46	0.01
Plot 3	0.41	0.43	0.42	0.01
NDVI Mean (month)	0.45	0.49	0.47	0.01

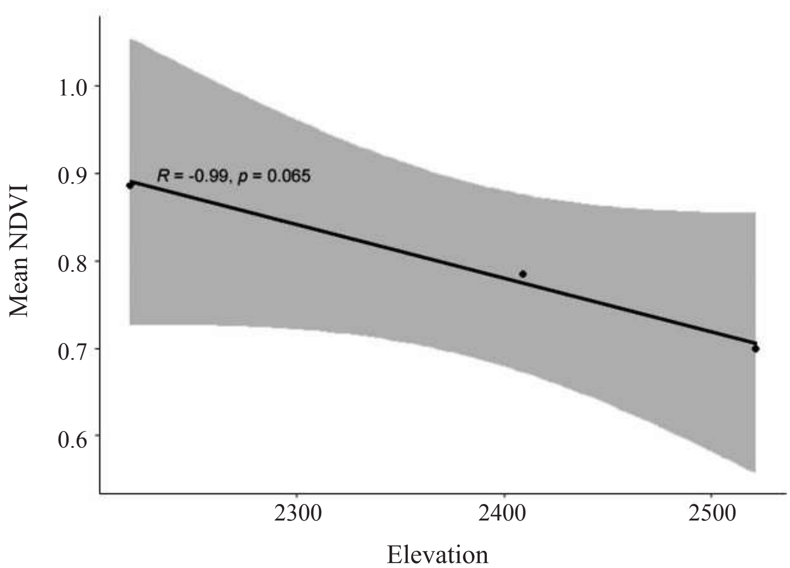

Fig. 4. Relationship between mean NDVI (October) and elevation (m.a.s.l.)

Similar values of AGB for cloud forest in Ecuador were found in the Río Guajalito Reserve, where other allometric equation was applied [48]. In such study, the estimated tree biomass for primary forest was 15160 kg/ha and we determined for the three plots the AGB amounts of 10717.8, 14529.11 and 8129.38 kg/ha.

A positive and strong relationship between NDVI and Chao1 was expected because it is known that between species richness and primary productivity there is a positive relationship [22], which in other forest studies has been estimated with NDVI as reflectance indicator [49]. In addition, these findings are consistent with the research results where the species richness was identified using remote sensing and NDVI [4, 13, 14, 16, 27, 50, 51]. This suggests that NDVI calculated from Landsat 8 images could be used to estimate species richness in TMCF when plot data are available.

Regarding the relationship between mean NDVI and elevation, its negative correlation means that when the elevation diminishes the NDVI increases. This can be explained with the fact that the number of individuals, also decreased with the altitude. Thus, in plot 3 the number of individuals was the lowest. According to [52], in the majority of altitudes the relationship between NDVI and elevation is positive. Nevertheless, in the range of altitude between 2200 to 2500 m.a.s.l. a negative relationship has been observed like in this research. A high NDVI showed in the lower elevation is because of a higher productivity owing to high temperature and sufficient water availability [53]. In addition, it is important to mention that plot 2 was catalogued as an ecotone because it can explain the NDVI decrease between plot 1 and plot 2.

Since species diversity is related to richness and abundance [54], a strong correlation between Shannon and Simpson indexes with NDVI was expected [20]. Nevertheless, the relationship was moderate and positive, like in other studies [5, 13, 55] where Shannon index and Simpson index were applied [4, 24, 26, 56]. Our correlations were not significant, hence, we recommended to sample more plots to discover the real relationship between these parameters. The plot size of 60 m × 60 m was established due to the fact that the pixel dimension of Landsat image is 30 m × 30 m and the small number of plots (3) was because of the difficulty in establishing extensive plots (60 × 60) homogeneous in terms of slope percentage. TMCF in the study area has a strong steep and very strong steep slope and the larger the plot, the less homogeneous it is [57]. Besides the TMCF usually are difficult to access [58]. Based on bibliography reviewed about positive and significant relationships between NDVI and diversity indices with a greater number of plots [4–6, 9, 15, 16, 19, 20, 24, 27, 52], the relationships in this study were also expected to be significant considering the difficulties mentioned.

Conclusion

Remote sensing, with the use of satellite images, has been playing an increasingly important role in forest conservation. Together with vegetation indexes have estimated richness, diversity and biomass over time. Within its advantages are high spatial-temporal resolution and easy global availability. On the other hand, its applicability is still limited by technical issues such as cloudiness in the images and the need for calibrations and corrections. Nevertheless, when overcome these limitations through appropriate techniques and the inclusion of environmental factors, diversity predictions can be more accurate.

By using field data and satellite imagery, our study has important implications in understanding the relationships between NDVI and alpha species diversity. We found a strong positive and significant relationship between species richness and NDVI. This relationship was analyzed in the two seasons of tropical forest and it was observed that in the rainy season the NDVI is higher, which is attributed to precipitation that offer better water availability and temperature to increase the photosynthetic rate and therefore productivity. The differences in seasonal NDVI are crucial to understand as it can be predicted how forests will respond to future climate changes. Finally, NDVI can be considered a useful method to estimate richness and biodiversity (using a greater number of plots) and even to detect ecotone as was the case in this research.

This paper has been supported by the RUDN University Strategic Academic Leadership Program. We also thank, El Cedral Ecolodge and the Universidad de las Fuerzas Armadas ESPE for the logistic support in Ecuador.

References

1. Jarvis A., Touval J.L., Schmitz M.C., Sotomayor L., Hyman G.G. Assessment of threats to ecosystems in South America // Journal for Nature Conservation. 2010. V. 18. No. 3. P. 180–188. doi: 10.1016/j.jnc.2009.08.003

2. Climate change and biodiversity in the tropical Andes / Eds. S. Herzog, R. Martínez, P. Jørgensen, H. Tiessen. Inter-American Institute for Global Change Research (IAI) and Scientific Committee on Problems of the Environment (SCOPE), 2011. doi: 10.13140/2.1.3718.4969

3. Llerena S., Arias P., Cueva J., Almeida G., Salazar C. Identifying priority management of Ecuadorian forests based on the environmental integrated assessment // E3S Web of Conferences. 2020. V. 169. Article No. 02015. doi: 10.1051/e3sconf/202016902015

4. Bawa K., Rose J., Ganeshaiah K.N., Barve N., Kiran M.C., Umashaanker R. Assessing biodiversity from space: An example from the Western Ghats, India // Ecology and Society. 2002. V. 6. No. 2. P. 7–11. doi: 10.5751/es-00434-060207

5. Feeley K.J., Gillespie T.W., Terborgh J.W. The utility of spectral indices from Landsat ETM+ for measuring the structure and composition of tropical dry forests // Biotropica. 2005. V. 37. No. 4. P. 508–519. doi: 10.1111/j.1744-7429.2005.00069.x

6. Foody G.M., Boyd D.S., Cutler M.E.J. Predictive relations of tropical forest biomass from Landsat TM data and their transferability between regions // Remote Sensing of Environment. 2003. V. 85. No. 4. P. 463–474. doi: 10.1016/S0034-4257(03)00039-7

7. Turner W., Spector S., Gardiner N., Fladeland M., Sterling E., Steininger M. Remote sensing for biodiversity science and conservation // Trends in Ecology and Evolution. 2003. V. 18. No. 6. P. 306–314. doi: 10.1016/S0169-5347(03)00070-3

8. Peng Y., Fan M., Song J., Cui T., Li R. Assessment of plant species diversity based on hyperspectral indices at a fine scale // Scientific Reports. 2018. V. 8. No. 1. P. 1–11. doi: 10.1038/s41598-018-23136-5

9. Madonsela S., Cho M.A., Ramoelo A., Mutanga O. Remote sensing of species diversity using Landsat 8 spectral variables // ISPRS Journal of Photogrammetry and Remote Sensing. 2017. V. 133. No. January 2018. P. 116–127. doi: 10.1016/j.isprsjprs.2017.10.008

10. Pesaresi S., Mancini A., Casavecchia S. Recognition and characterization of forest plant communities through remote-sensing NDVI time series // Diversity. 2020. V. 12. No. 8. Article No. 313. doi: 10.3390/D12080313

11. Rouse J., Hass R., Schell J., Deering D. Monitoring vegetation systems in the Great Plains with ERTS // NASA Goddard Space Flight Center 3d ERTS-1 Symp. 1974. V. 1. P. 309–317. doi: 10.1021/jf60203a024

12. Pettorelli N. The normalized difference vegetation index. United KIngdom: Oxford University Press, 2013. 43 p.

13. Pau S., Gillespie T.W., Wolkovich E.M. Dissecting NDVI-species richness relationships in Hawaiian dry forests // Journal of Biogeography. 2012. V. 39. No. 9. P. 1678–1686. doi: 10.1111/j.1365-2699.2012.02731.x

14. Fairbanks D., McGwire K. Patterns of floristic richness in vegetation communities of California: Regional scale analysis with multi-temporal NDVI // Global Ecology and Biogeography. 2018. V. 13. No. 3. P. 221–235.

15. Wang R., Gamon J. Remote sensing of terrestrial plant biodiversity // Remote Sensing of Environment. 2019. V. 231. P. 1–15. doi: 10.1016/j.rse.2019.111218

16. Pouteau R., Gillespie T.W., Birnbaum P. Predicting tropical tree species richness from normalized difference vegetation index time series: The devil is perhaps not in the detail // Remote Sensing. 2018. V. 10. No. 5. P. 11–13. doi: 10.3390/rs10050698

17. Wang R., Gamon J.A., Montgomery R.A., Townsend P.A., Zygielbaum A.I., Bitan K., Tilman D., Cavender-Bares J. Seasonal variation in the NDVI-species richness relationship in a prairie grassland experiment (cedar creek) // Remote Sensing. 2016. V. 8. No. 2. doi: 10.3390/rs8020128

18. Gamon J.A., Field C.B., Goulden M.L., Griffin K.L., Hartley E., Joel G., Peñuelas J., Valentini R. NDVI canopy structure photosynthesis // Ecological Applications. 1995. V. 5. No. 1. P. 28–41.

19. Freitas S.R., Mello M.C.S., Cruz C.B.M. Relationships between forest structure and vegetation indices in Atlantic Rainforest // Forest Ecology and Management. 2005. V. 218. P. 353–362. doi: 10.1016/j.foreco.2005.08.036

20. Cabacinha C.D., de Castro S.S. Relationships between floristic diversity and vegetation indices, forest structure and landscape metrics of fragments in Brazilian Cerrado // Forest Ecology and Management. 2009. V. 257. No. 10. P. 2157–2165. doi: 10.1016/j.foreco.2009.02.030

21. Skidmore A.K., Oindo B.O., Said M.Y. Biodiversity assessment by remote sensing // Proceedings of the 30th International Symposium on Remote Sensing of the Environment: Information for Risk Management and Sustainable Development, 2003. P. 1–4.

22. Currie D. The university of Chicago energy and large-scale patterns of animal- and plant-species richness // The American Naturalist. 1991. V. 137. No. 1. P. 27–49.

23. Hashemi S.A., Fallah Chai M.M., Bayat S. An analysis of vegetation indices in relation to tree species diversity using by satellite data in the northern forests of Iran // Arabian Journal of Geosciences. 2013. V. 6. No. 9. P. 3363–3369. doi: 10.1007/s12517-012-0576-8

24. Madonsela S., Cho M.A., Ramoelo A., Mutanga O., Naidoo L. Estimating tree species diversity in the savannah using NDVI and woody canopy cover // International Journal of Applied Earth Observation and Geoinformation. 2018. V. 66. No. January. P. 106–115. doi: 10.1016/j.jag.2017.11.005

25. Kiran G.S., Mudaliar A. Remote sensing & geoinformatics technology in evaluation of forest tree diversity // Pelagia Research Library. 2012. V. 2. No. 3. P. 237–242.

26. Arekhi M., Yılmaz O.Y., Yılmaz H., Akyüz Y.F. Can tree species diversity be assessed with Landsat data in a temperate forest? // Environmental Monitoring and Assessment. 2017. V. 189. No. 11. P. 1–14. doi: 10.1007/s10661-017-6295-6

27. Mohammadi J., Shataee S. Possibility investigation of tree diversity mapping using Landsat ETM+ data in the Hyrcanian forests of Iran // Remote Sensing of Environment. 2010. V. 114. No. 7. P. 1504–1512. doi: 10.1016/j.rse.2010.02.004

28. Aguirre N., Añazco M., Ordoñez L., Pekkarinen A., Ramirez C., Román R.M., Sánchez G., Velasco C. Metodologia para el desarrollo del estudio piloto de la ENF en conformidad con el mecanismo REDD+. Quito: MAE y FAO, 2010. 59 p.

29. Phillips O.L., Baker T.R., Brienen R., Feldpausch T.R. Field manual for plot establishment and remeasurement. South America: RAINFOR, 2010. 21 p.

30. MECN. Áreas Naturales del Distrito Metropolitano de Quito: Diagnóstico Bioecológico y Socioambiental. V. 53. 1-st ed. Quito: Imprenta Nuevo Arte, 2010. 52 p.

31. Jorgensen P., Ulloa C., Maldonado C. Riqueza de plantas vasculares // Botánica Económica de Los Andes Centrales. 2006. P. 37–50.

32. Tropicos. Missouri Botanical Garden [Internet resource] https://tropicos.org/home (Accessed: 04.05.2021)

33. Hammer O., Harper D., Ryan P. PAST: Paleontological statistics software package for education and data analysis // Palaeontologia Electronica. 2001. V. 4. No. 1. P. 9.

34. Statistical software for insight-driven improvement [Internet resource] https://www.jmp.com/en_us/home.html (Accessed: 15.01.2022)

35. Colwell R. Biodiversity: concepts, patterns, and measurement. The Princeton guide to ecology / Eds. S.A. Levin, S.R. Carpenter, H.Ch.J. Godfray, A.P. Kinzig, M. Loreau, J.B. Losos, B. Walker, D.S. Wilcove. Princeton: Princeton University Press, 2009. P. 257–263. doi: 10.1515/9781400833023.257

36. Chao A. Nonparametric estimation of the number of classes in a population // Scandinavian Journal of Statistics. 1984. V. 11. No. 4. P. 265–270. doi: 10.2307/4615964

37. Colwell R.K., Coddington J.A. Estimating terrestrial biodiversity through extrapolation. // Philosophical Transactions of the Royal Society of London Series B, Biological Sciences. 1994. V. 345. No. 1311. P. 101–118. doi: 10.1098/rstb.1994.0091

38. Shannon C. A Mathematical theory of communication // Bell System Technical Journal. 1948. V. 27. No. 4. P. 623–656. doi: 10.1002/j.1538-7305.1948.tb00917.x

39. Shannon C., Weaver W. The mathematical theory of communication. Urbana: The University of Illinois Press, 1964. 131 p.

40. Alvarez E., Duque A., Saldarriaga J., Cabrera K., de las Salas G., del Valle I., Lema A., Moreno F., Orrego S., Rodríguez L. Tree above-ground biomass allometries for carbon stocks estimation in the natural forests of Colombia // Forest Ecology and Management. 2012. V. 267. P. 97–308. doi: 10.1016/j.foreco.2011.12.013

41. Rodríguez M., Sibille A. Manual de identificación de especies forestales de la subregión andina. INIA-OIMT, 1996. 489 p.

42. Llerena S., Tarko A., Kurbatova A., Kozhevnikova P. Assessment of carbon dynamics in Ecuadorian forests through the mathematical spatial model of global carbon cycle and the normalized differential vegetation index (NDVI) // E3S Web Conf. 2019. V. 96. Article No. 02002. doi: 10.1051/e3sconf/20199602002

43. Cartaya Ríos S., Zurita Alfaro S., Rodríguez Ríos E., Montalvo Párraga V. Comparación de técnicas para determinar cobertura vegetal y usos de la tierra en áreas de interés ecológico, Manabí // UD y La Geomática. 2014. V. 9. P. 5–17.

44. Kafria V., Albanakis K., Oikonomidis D. Flood susceptibility assessment using G . I . S . An example from Kassandra Peninsula, Grrece. Proc. 10th Int. Congr. Hell. Geogr. Soc., 2014. P. 22–24.

45. RStudio: Integrated Development Environment for R. RStudio Team. PBC [Internet resource] https://www.rstudio.com (Accessed: 05.15.2021).

46. Ledo A., Condés S., Alberdi I. Forest biodiversity assessment in Peruvian Andean Montane cloud forest // Journal of Mountain Science. 2012. V. 9. No. 3. P. 372–384. doi: 10.1007/s11629-009-2172-2

47. Khaine I., Woo S.Y., Kang H., Kwak M.J., Je S.M., You H., Lee T., Jang J., Lee H.K., Lee E., Yang L., Kim H., Lee J.K., Kim J. Species diversity, stand structure, and species distribution across a precipitation gradient in tropical forests in Myanmar // Forests. 2017. V. 8. No. 8. P. 1–15. doi: 10.3390/f8080282

48. Mapstone E. Carbon sequestration in the cloud forest: A comparative evaluation of aboveground biomass carbon stock potential in the Río Guajalito Reserve // Independent Study Project. 2017. P. 1–29.

49. Tucker C.J., Sellers P.J. Satellite remote sensing of primary production // International Journal of Remote Sensing. 1986. V. 7. No. 11. P. 1395–1416. doi: 10.1080/01431168608948944

50. Nagendra H., Rocchini D., Ghate R., Sharma B., Pareeth S. Assessing plant diversity in a dry tropical forest: Comparing the utility of landsat and ikonos satellite images // Remote Sensing. 2010. V. 2. No. 2. P. 478–496. doi: 10.3390/rs2020478

51. Gillespie T. Predicting woody-plant species richness in Tropical Dry Forest: A case study from south Florida, USA // Ecological Applications. 2005. V. 15. No. 1. P. 27–37.

52. Zhan Z., Liu H., Li H., Wu W., Zhong B. The relationship between NDVI and terrain factors – A case study of chongqing // Procedia Environmental Sciences. 2012. V. 12. P. 765–771. doi: 10.1016/j.proenv.2012.01.347

53. Liu L., Wang Y., Wang Z., Li D., Zhang Y., Qin D. Elevation-dependent decline in vegetation greening rate driven by increasing dryness based on three satellite NDVI datasets on the Tibetan Plateau // Ecological Indicators. 2019. V. 107. No. 5. P. 1–11. doi: 10.1016/j.ecolind.2019.105569

54. Sanjit L., Bhatt D. Commentary how relevant are the concepts of species diversity and species richness? //

Journal of Bioscience. 2005. V. 30. No. 5. P. 557–560. doi: 10.1007/BF02703552

55. Foody G.M., Cutler M.E.J. Mapping the species richness and composition of tropical forests from remotely sensed data with neural networks // Ecological Modelling. 2006. V. 195. No. 1–2. P. 37–42. doi: 10.1016/j.ecolmodel.2005.11.007

56. Meng J., Li S., Wang W., Liu Q., Xie S., Ma W. Estimation of forest structural diversity using the spectral and textural information derived from SPOT-5 satellite images // Remote Sensing. 2016. V. 8. P. 125. doi: 10.3390/rs8020125

57. Van den Meerssche S. Carbon storage on an elevational gradient on the west side of the Andes (Ecuador). Ghent University: Faculty of Bioscience Engineering, 2020. 74 p.

58. Llerena S., Kurbatova A., Grigorets E. Carbon sequestration in tropical montane cloud forests // Environment and Human: Ecological Studies. 2021. V. 11. No. 3. P. 377–397. doi: 10.31862/2500-2961-2021-11-3-377-3977