Bulletin of the *Transilvania* University of Braşov
Series II: Forestry • Wood Industry • Agricultural Food Engineering • Vol. 11 (60) No. 1 - 2018

PHOTOSYNTHETIC ACTIVITY AND CANOPY HEIGHT MODEL DETERMINED BY UAV RGB AND IR CLOSE-RANGE REMOTE-SENSING IN THE HIGH ANDEAN POLYLEPIS RELICT FOREST, ECUADOR

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Abstract: *Unmanned aircraft systems are broadly used for ecological research and conservation efforts. The goal of this study was to document the status quo of the photosynthetic activity, spatial distribution and some of the biometric characteristics of the High Andean Polylepis relict forest located in the "Reserva de Producción de Fauna Chimborazo". Using RGB and IR sensors mounted on Unmanned Aerial Vehicles (UAVs), a multispectral image was obtained to calculate the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). From this image, a cloud of points was generated to determine the Digital Surface Model (DSM) and Digital Terrain Model (DTM). Layer of NDVI values was ranked between 0.708 and - 0.539 and layer of EVI values was ranked between 0.00059 and - 0.00021 to consider all of the coverage types (forest cover, herbaceous vegetation and rocky outcrop), with which it was demonstrated that the photosynthetic activity in the study area is low. The Canopy Height Model (CHM) was obtained as difference between DSM and DTM. The methods described in this study could be used to document the conservation status of natural protected areas and to support biomass calculations for studies of carbon sequestration in the high Andean forests of Ecuador.*

Key words: *conservation, Polylepis, Andean forest, close-range UAV remote sensing, photosynthetic activity, canopy height, land cover.*

1. Introduction

Forests as ecosystems, enable several ecological and social functions, which range from the provision of water and shelter for wildlife to human-related needs, such as recreation [4], [20].

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Forests also provide important material and non-material services, such as medicinal plants, materials for handicrafts, and a natural context for practicing traditional beliefs [8], [39]. Sustainable management of forests requires timely and accurate information which can be provided by the use of geospatial technologies. Such technologies have been widely used and valued, to identify critical zones at different scales in the forest cover [23]. In recent years, new techniques for forest monitoring have been developed, many of which are based on the use of remote sensing methods that allow the instantaneous representation of spatial information. Some of these refer to the interpretation of aerial multispectral photographs (panchromatic, color and infrared), videography and digital classification of satellite images. In addition, a series of scientifically-designed satellites are used to periodically collect information about the electromagnetic radiation reflected by the Earth surface such as those of the Spot and Landsat missions [32].

More recently, a growing interest in the use of UAVs has been showed by the research community [40]. The use of UAVs such as drones is spreading across many domains including delivery, communications, surveillance and in emergency operations [1], [26].

The UAV technology has been used in various areas in order to coordinate the processes of data collection, being of great utility in forestry, where it contributed by providing useful data for the forest management activities [2], [27]. The main advantage that the UAVs may provide is a high spatial and temporal resolution [15], [44]. In addition, it is possible to repeat the flights systematically and to compare the images of different moments using specific software tools, which lead to more reliable results [21].

Ecuador spreads across an area of 24,898,396 hectares, being characterized by a coverage of natural vegetation of approximately 50% standing for 12,261,997 hectares [17]. According to the Ecosystem Map of the Continental Ecuador [12], the country holds 91 ecosystems, of which 65 are woodlands, 11 are shrublands and the remaining 15 are of herbaceous nature, reflecting a great floristic diversity. Among the ecosystems which are considered to be the most important for the research in Ecuador are the high Andean forests [17]. This group contains several ecosystems including the *Polylepis* relict forest which is located inside the “Reserva de Producción de Fauna Chimborazo”, where the dominant species is the *Polylepis reticulata* Hieron [7].

Ecologists and conservation practitioners have proven the efficiency of incorporating the emerging technologies into field data collection efforts [30]. UAVs belong to an emerging technology that allows the acquisition of remote sensing images with a resolution in the range of centimeters [45]. Several indices derived from satellite imagery provide relatively cost-efficient solutions to achieve this goal with NDVI placed among the most used ones [29]. Canopy height is an important parameter required in forest inventories as well as in monitoring and modeling activities [38]. It is an ecological measure that provides essential information related to ecological, hydrological, biophysical, micro-meteorological, and agronomic processes in natural vegetation and agricultural crops [6].

The preference for UAVs as a support for aerial photographs in high resolution, lies in its economic benefits, availability, maneuverability and accuracy as described by Peña et al. (2014) [28]. To preserve the highly valued, protected ecosystems, intrusion should be limited to the strictly needed activities [14]. This means that even research endeavors should make use of the non-intrusive tools and methods, contributing to the preservation of the protected areas while being able to provide useful information to sustain their management [10].

Values of NDVI depend on the reflectance peak of vegetation in the infra-red [41]. Furthermore, NDVI is highly correlated with photosynthetically active radiation absorbed by the plant canopy, photosynthetic capacity, net primary production, leaf area index, fraction of absorbed photo-synthetically active radiation, carbon assimilation and evapotranspiration [3], [43]. Therefore, it constitutes an informative proxy to monitor photosynthesis over time, and to perform temporal and spatial vegetation surveys [22]. A refined form of NDVI is nowadays being used - EVI. Its adaptation has improved NDVI sensitivity in dense vegetation regions, having also a better performance in minimizing the soil and atmosphere influences [11].

The goal of this study was to document the status quo of the photosynthetic activity, spatial distribution and some of the biometric characteristics of the High Andean *Polylepis* relict forest located in the "Reserva de Producción de Fauna Chimborazo". To this end, the objectives of the study were set to: (i) estimating the photosynthetic activity by the means of NDVI and EVI indexes, using UAV mounted RGB and IR sensors and close-range remote-sensing techniques and (ii) characterizing the spatial features of this forest by the means of canopy closure and canopy height derived from the remote-sensed data. In a first step, the results will be used to characterize the status quo of the forest and, on short-medium term, they could serve as a reference dataset to be used in temporal comparison of the area, following that other flights will be deployed at regular intervals.

2. Materials and Methods

2.1. Study Area

The study covered an area located at 1°54'02''84 S 78°88'39''56 W, 4300 m above sea level (Figure 1), near the Chimborazo volcano, at the boundary of Bolivar and Chimborazo provinces, in the "Reserva de Producción de Fauna Chimborazo" (Figure 1b), which is one of the 51 protected areas of Ecuador, a country located in the South America (Figure 1a). In the High Andean landscapes, the *Polylepis* forests are characterized by small covered patches dispersed across the territory. Such forests are characterized by very low heights, increased age, and visually-appealing trees due to their contorted trunks (Figure 1c).

2.2. Experimental Design and Field Data Collection

To carry out the aerial photogrammetric survey, as well as the processing and post processing of information, the study was divided into 2 stages: a field phase and an office phase, both carried out in November of 2017. While the forest itself covers an area of about 0.5 ha [7], the flights were designed to cover a buffer zone of more than 100 hectares (Figure 1d).

A number of 2 flights were carried out, of which one used an RGB (Red, Green and Blue) camera while the other used an IR (Infrared Radiation) camera, covering a total of 188.4 ha and 250.66 ha respectively on each flight.

The equipment used to collect the information included:

- an UAV fixed-wing airplane type (E384 de event38) equipped with a high-resolution camera and an integrated Global Positioning System (GPS);
- a NX1100 Samsung RGB, 21.3 MP camera;
- a Canon PowerShot SX260 HS equipped with an NGB sensor of 12 MP;
- a precision Global Navigation Satellite System (GNSS) - brand SOKKIA model GRX2;
- an objective of radiometric calibration gray to 18%, an anemometer and an altimeter.

In total, 4 Ground Control Points (GCPs) were defined, marked in the field (Table 1 and Figure 2a) and precisely located using the Real Time Kinematic (RTK) mode, to serve for adjustments in the post-processing phase of the orthophotomosaic generation. In the field, each GCP was marked crosswise to get an efficient recognition by the software in the photogrammetric process.

Table 1

Control points for photogrammetric restitution

Ground Control Point	**Lat**	**Long**	**Ellipsoidal Height**
PC1	-1°53'76''23	-78°88'09''49	4270.958
PC2	-1°53'97''84	-78°88'19''17	4300.166
PC3	-1°54'11''24	-78°88'35''51	4306.928
PC4	-1°54'24''97	-78°88'21''75	4260.362

During the preparation and calibration stage, the usual tasks such as assembling the UAV, calibration of the remote control, connection by telemetry, load revision and balance point, were carried out. Based on the reference coordinates and the previously marked control points, the flight plans were defined in the flight planning software. The pattern of the two flights was the same and was planned to cover the area of interest at a flight height of 200 meters. Then, the automatic flights assisted by telemetry were carried out according to the generated flight pattern (Figure 1d). Two photographic sessions were performed, obtaining a total of 133 photos with the RGB camera and 278 photos with the IR camera.

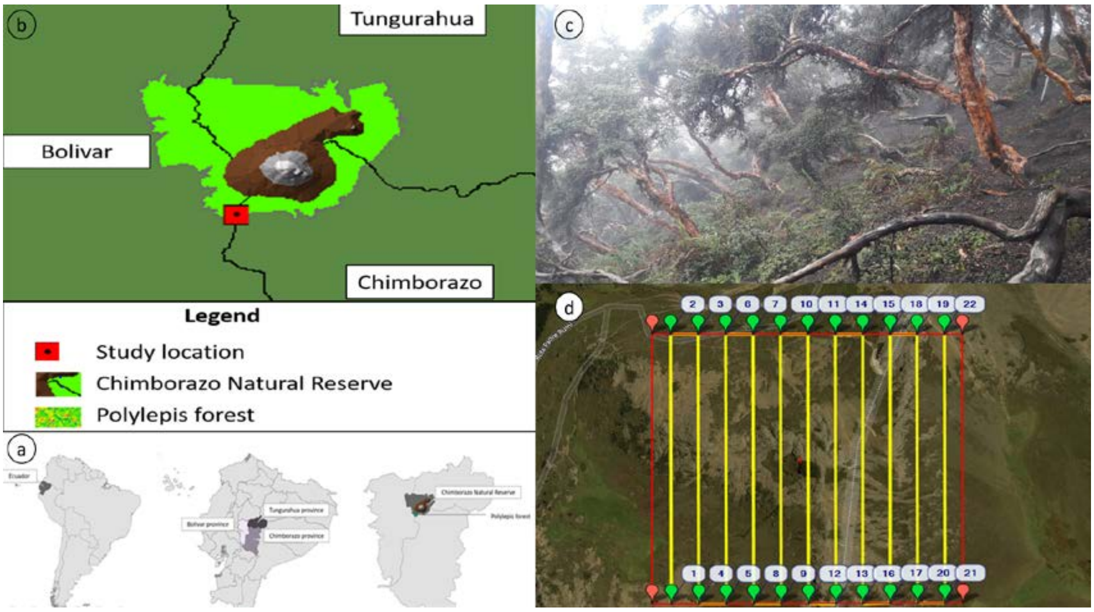

Fig. 1. *Study location and coverage of the flights: a) - general location within South America, Ecuador and province; b) - detail of the study area located near the volcano Chimborazo; c) - a snapshot of the Polylepis forest (original); d) - area covered by the flights*

Fig. 2. *Field-marking of the GCPs*

2.3. Data Analysis

A pre-evaluation of the photos was carried out, including a calibration and an initial control prior to the generation of the orthophotomosaic. Of the total of 133 photos taken on the RGB flight, 131 passed the quality control (98.5%) and were selected for the orthorectification stage. In the case of the IR camera, all of 278 photos taken passed the quality control.

The initial processing and calculation of optimal resolution was carried out in relation to the height flight and the position data of each photo, yielding a resolution of 7.27 cm/pixel with the data set obtained from the RGB camera and of 9.37 cm/pixel with the data obtained from the IR camera. Data processing was done using the WGS 84 UTM coordinate system, area 17S. The relative height of the terrain was calculated based on the geolocation data included in the photos. A cloud of points was generated and both, the filtered point cloud and the densified point cloud were created in the .LAS format. A Digital Surface Model (DSM) was generated based on the structure of the point cloud, as a continuous numerical model representing the heights of the ground and of the surface objects. It was obtained from the photogrammetric processing carried on in the Pix4D software [25]. A Digital Elevation Model (DEM) and a Digital Terrain Model (DTM) including a set of layers and numerical data were built by filtering the ground points from the raw point clouds. Orthophotomosaics were generated after an orthorectification process of images, with a quality report reflecting a mean square error of 0.076 m in georeferencing, and 0.01 m in the RGB and NGB orthophotomosaics, respectively. Multispectral aerial images where obtained from the cameras installed on the UAV.

To estimate the areas characterized by the greatest photosynthetic activity, in a first step, standard vegetation wavebands of blue (450 nm), green (550 nm), red (650 nm) and near infrared (770 nm) were used. Each filter has a bandpass of approximately 25 nm, resulting in images with a spatial resolution of cca. 9 cm and a total image coverage of 100 ha. Geometric and radiometric distortions induced by the camera were corrected in the set of images using the digital photogrammetric treatment. The process mentioned above was done using the Pix4D software.

The NDVI and EVI were used to establish the areas of greatest photosynthetic activity. The work of Rose et al. (1973) [35] was used to calculate the NDVI as NDVI = IR –R / IR + R (where IR is the Infrared Band and R is the Red Band). EVI was calculated according to the work of Jiang et al. (2008) [13] as EVI = 2.5 × (IR-R) / (IR+6R – 7.5 B+1), where B is the Blue Band and R is the Red Band).

The positive values of indexes indicate that it is greening or that it has greater vegetation vigor, and values close to zero mean neutral values or values without significant changes [37].

The estimation of canopy height was based on the general procedure proposed by Tuominnen (2015) and Zarco (2014) [42], [46]. The map of vegetation and land use of the study area was elaborated by a supervised classification of the multispectral orthophoto, using the ENVI software, by implementing the following steps:

- A classification scheme was established based on the LEVEL II classification of the MAE (2016) [18] regarding the land use and land cover, resulting in the identification of 4 classes in the data set: native forest, herbaceous vegetation, areas without plant cover, rocky outcrop;

- A set of ground-known representative pixels of each of the four classes were used to determine the training areas;
- The spectral reparability between the classes was calculated in order to identify their statistical quality. To this end, a transformed divergence index was used [33], which takes values in the range between 0 and 2, with values greater than 1 pointing a good reparability, and with values lower than 1 advising for merging the two studied classes into one;
- The supervised classification of the image was carried out using the Maximum Likelihood Algorithm as described in Richards (2005) [34];
- A process to enable smoothing and aggregation was applied in order to eliminate the noise and eliminate units of smaller size than the minimum chartable units;
- The product of classification was saved as a shapefile, followed by a generalization of the map using as a measure the minimum mapping unit according to Table 2 [31]. For the scale used in this study (close to 1:1000) the minimum area corresponded to 16 m^2);
- Following these steps, an information layer corresponding to the land use classification of the study area was obtained.

Table 2

NDVI values for coverage areas according to the proposed classification legend

Coverage class	NDVI values			
	Maximum	**Minimum**	**Average**	**Standard deviation**
a) Forest cover	0.708	0.003	0.13	±0.07
b) Herbaceous vegetation	0.56	0.003	0.05	±0.04
c) Rock outcrop	0.62	-0.53	-0.10	±0.07
d) Naked soil	0.395	-0.39	-0.08	±0.045

3. Results and Discussion

The obtained orthophotomosaic was characterized by a resolution of 9 cm and 4 spectral bands (Red-Band 1, Green-Band 2, Blue-Band 3, Infrared-Band 4) characterized by the features shown in Figure 3. The multispectral image (Figure 3) was built using the process known as the Layer Stack or Union of Bands [24].

Fig. 3. *Orthophotomosaic area of interest (AOI) in RGB (left) and IR (right)*

According to the calculation using the formula proposed by Rose et al. (1974) [36] of NDVI, values ranging between 0.708 and -0.539 was obtained for the entire area of study, including all types of cover. Table 4 shows the NDVI values of coverage areas according to the proposed classification system, while Figure 4 shows the statistical information and spatial distribution of the NDVI values by land cover classes.

The value of NDVI for the rocky outcrop class (Figue 4c, left) could be the result of the spectral mixture within this unit, which could be explained by the presence of some pixels inside the unit standing for vegetation, therefore reflecting high values of NDVI. However, the statistical distribution showed a predominance of values lower than 0 (Figure 4c, right). As the soil is known not to have photosynthetic activity [9].

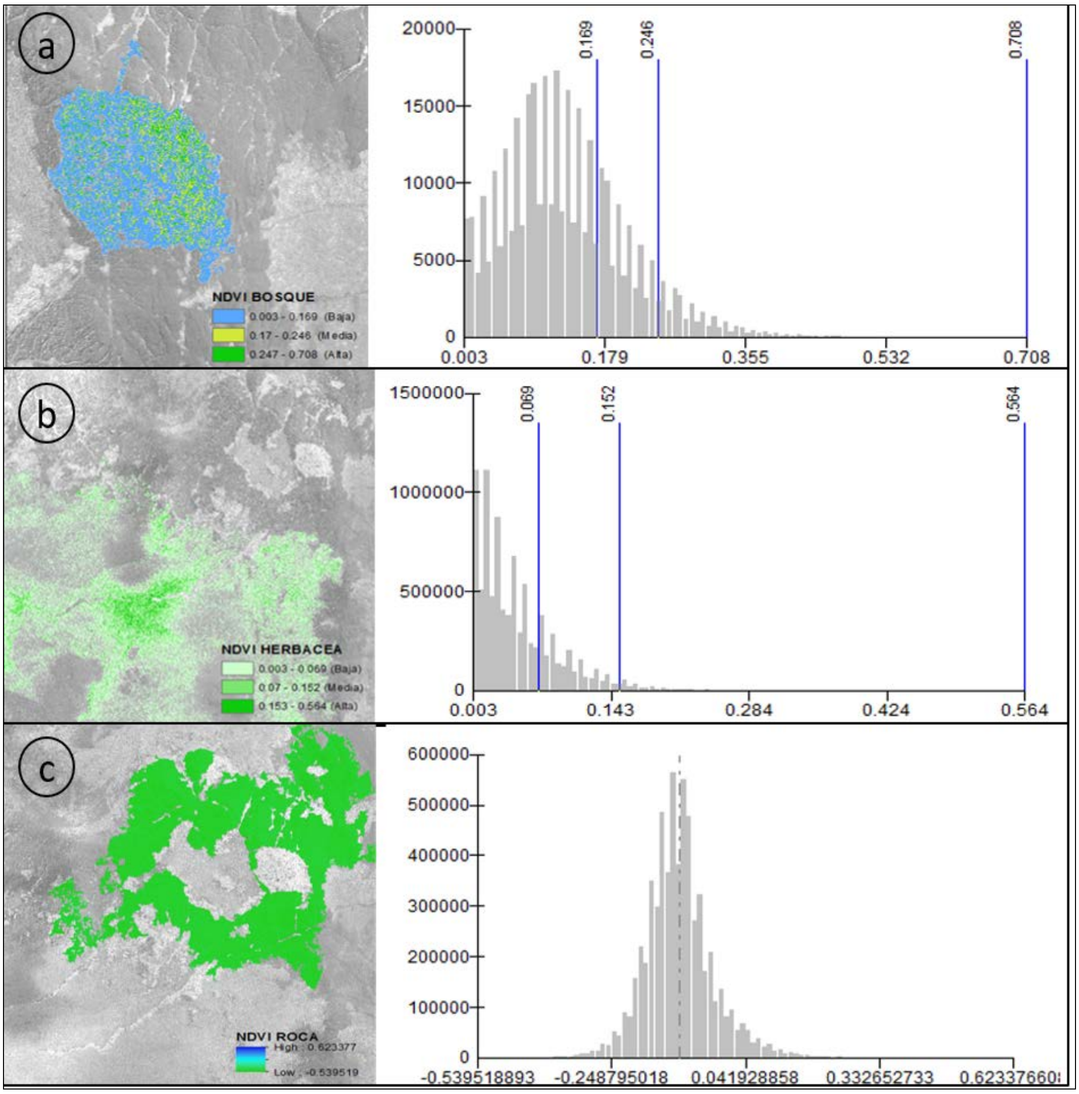

Fig. 4. *Statistical information and spatial distribution of NDVI values by classes: a) - forest cover; b) - herbaceous vegetation; c) - rocky outcrop*

On the other hand, according the formula proposed by Liu and Huete (1995) [16] for EVI was obtained the statistical information and spatial distribution of all types of cover classes as given in Table 3 and Figure 5.

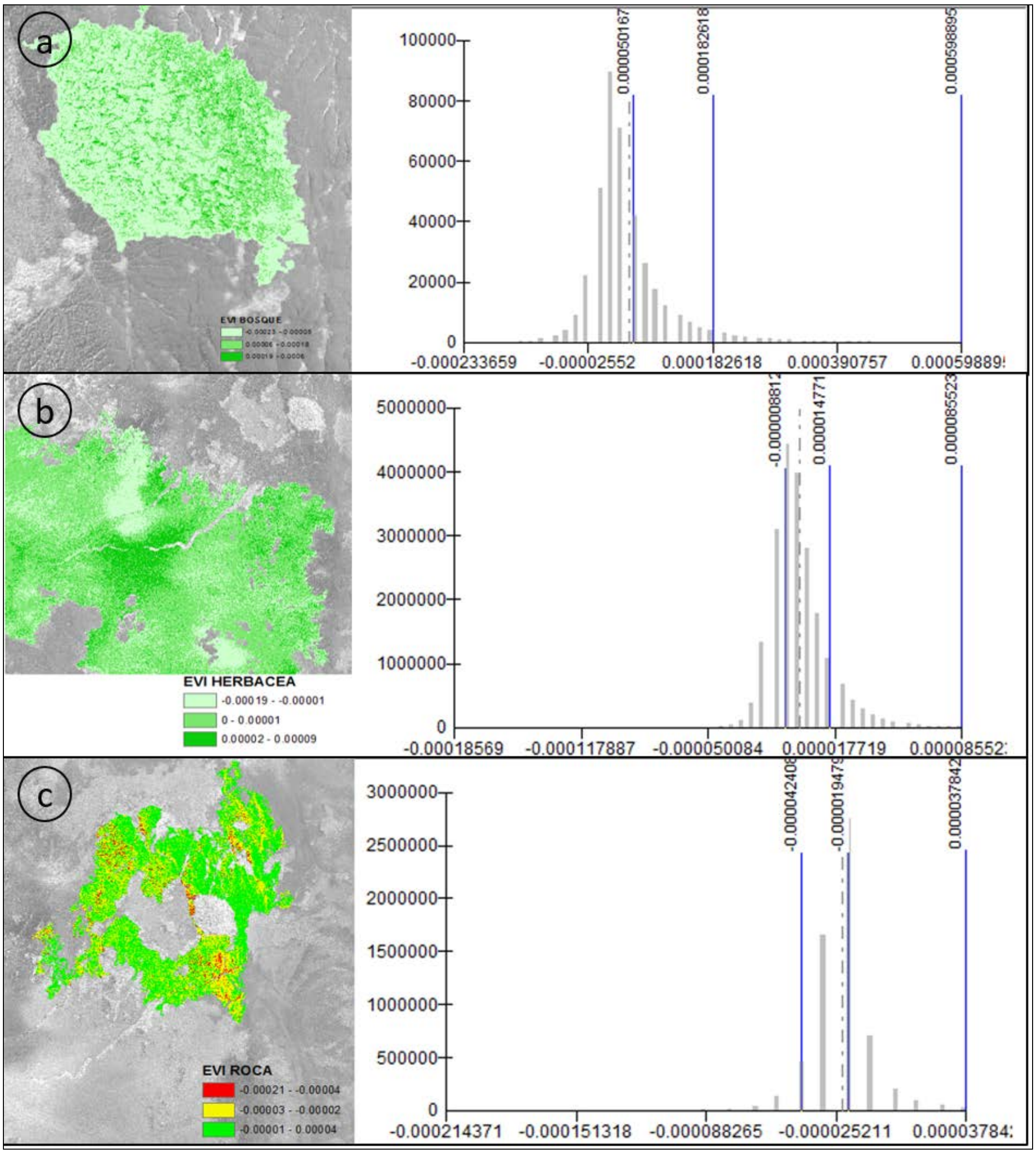

Fig. 5. *Statistical information and spatial distribution of EVI values by classes: a) - forest cover; b) - herbaceous vegetation; c) - rocky outcrop.*

Table 3

EVI values of coverage areas according to the proposed classification system

Coverage class	EVI Values			
	Maximum	Minimum	Average	Standard deviation
a) Forest cover	0.00059	-0.00023	0.0004	±0.00007
b) Herbaceous vegetation	0.0009	-0.00019	0	±0.002
c) Rock outcrop	0.00004	-0.00021	-0.00002	±0.00001
d) Naked soil	0.000012	-0.000034	-0.000015	±0.0000075

A layer of EVI values ranging between 0.00059 and -0.00023 was obtained for the entire study area that included all types of forest cover (including shrub vegetation), paramo (herbaceous vegetation), rock and soil. As known, low EVI values tend to occur in semi-arid or low-moisture areas [5]. The NDVI values ranked between 0.708 and 0.003 for the forest cover class. These results were compared with the results reported by Salinas et al. (2017) [37].

Although the expectations were to have a high photosynthetic activity due to the presence of 6252 individuals belonging to 18 species in the *Polylepis* relict forest, spread over 0.5 ha [7], the results demonstrate that the photosynthetic activity in the study area was low with the values of forest cover having a major concentration in the range of 0.003 to 0.246. The maximum value was 0.708 being close to that of 0.8 reported by Salinas et al. (2017) [37] and which was clearly associated with the areas of greatest vegetation cover. On the other hand, the average value was of 0.13 (standard deviation ±0.07), and it was compared with results reported by Gillespie et al. (2018) [9] who found a mean value of 0.511 (standard deviation ±0.074) in case of the Santa Monica Mountains National Recreation Area (SAMO) and a mean value of 0.399 (standard deviation ±0.111) in case of Channel Islands National Park (CHIS), showing that our results had a major similarity with those of coast vegetation (SAMO). The EVI values ranked between 0.00059 and -0.00023 in the case of forest coverage class, where we found the majority of values between -0.000025 and 0.00018. The average of EVI values was 0.0004 and standard deviation was of ±0.00007.

The values of NDVI in this study were different from those of EVI, which is related to what was stated by Matsushita et al. (2007) [19]. Therefore, it is the soil adjustment factor in the EVI which makes it much more sensitive to the direct effect compared to NDVI, while both the EVI and the NDVI can be influenced by the indirect effect of the topography.

The supervised classification of the multispectral orthophoto, resulted into a map of land cover in which four main classes have been identified: rocky outcrop (15.44% of the area), areas without vegetation cover (27.34% of the area), native forest (3.77% of the area) and herbaceous vegetation (53.45% of the area). The pixel values for each class showed a good separability in all the bands with values ranging between 153 and 181 for all the classes. The basic descriptive statistics of the values per class for the 4 spectral bands are shown in Table 4.

Table 4

Average values of the pixels and standard deviation of the 4 classes including 4 spectral bands

	Class: Forest cover	
Bands	**Average**	**Standard deviation**
Band 1: Red	181,470502	±34,769848
Band 2: Green	168,282870	±31,124958
Band 3: Blue	156,260080	±31,348127
Band 4: Near infrared	156,683087	±12,237709
	Class: Herbaceous vegetation	
Bands	**Average**	**Standard deviation**
Band 1: Red	173,273293	±35,486439
Band 2: Green	163,537751	±33,069896
Band 3: Blue	153,246415	±31,960585
Band 4: Near infrared	155,005723	±11,661273
	Class: Rocky outcrop	
Bands	**Average**	**Standard deviation**
Band 1: Red	171,427530	±32,727871
Band 2: Green	162,049483	±29,820629
Band 3: Blue	151,165802	±29,922165
Band 4: Near infrared	154,488252	±11,326354
	Class: Naked soil	
Bands	**Average**	**Standard deviation**
Band 1: Red	176,099649	±30,860827
Band 2: Green	166,903358	±29,340723
Band 3: Blue	153,994504	±29,527143
Band 4: Near infrared	155,473101	±11,893077

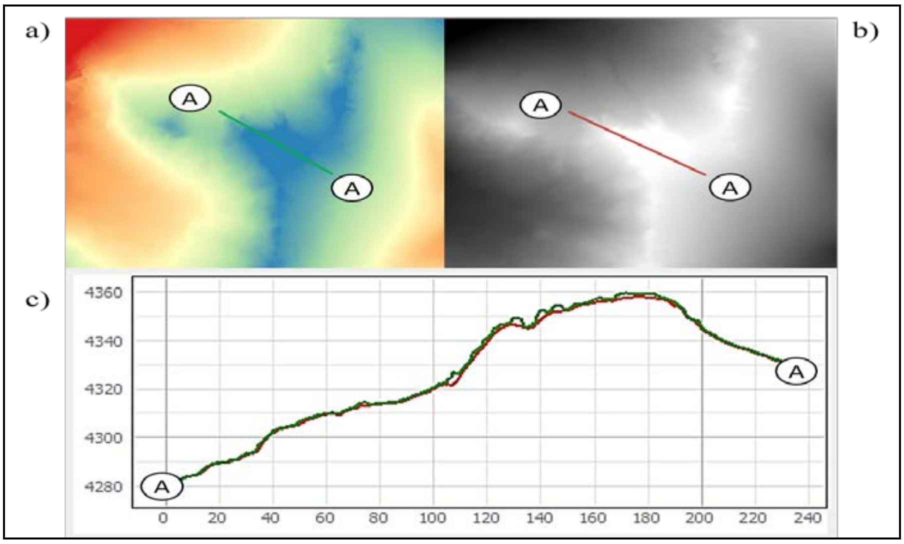

Fig. 6. *Estimates of canopy height: a) - Digital Surface Model; b) - Digital Terrain Model; c) cut A - A indicating the differences in height (red = DEM heights, green = DSM heights)*

The Canopy Height Model (CHM) was created by subtracting the DSM from the DTM like in the study of Nguyet (2012) [24]. Following the calculations, the maximum value of CHM was of 4361.5 m above sea level, this data being similar to the 4300 m above sea level for the *Polylepis* relict forest as reported by Castillo et al. (2017) [7]. Also, the estimated time to generate the CHM using multispectral images collected by UAV was of 5 days, out of which 4 days were used to obtain multispectral images, MDS, MDT, CHM, NDVI and EVI.

In comparison, the manual method to obtain similar products was estimated at 4 months as reported by Castillo et al. (2017) [7], meaning that the use of the UAVs to collect data is more efficient than the manual method.

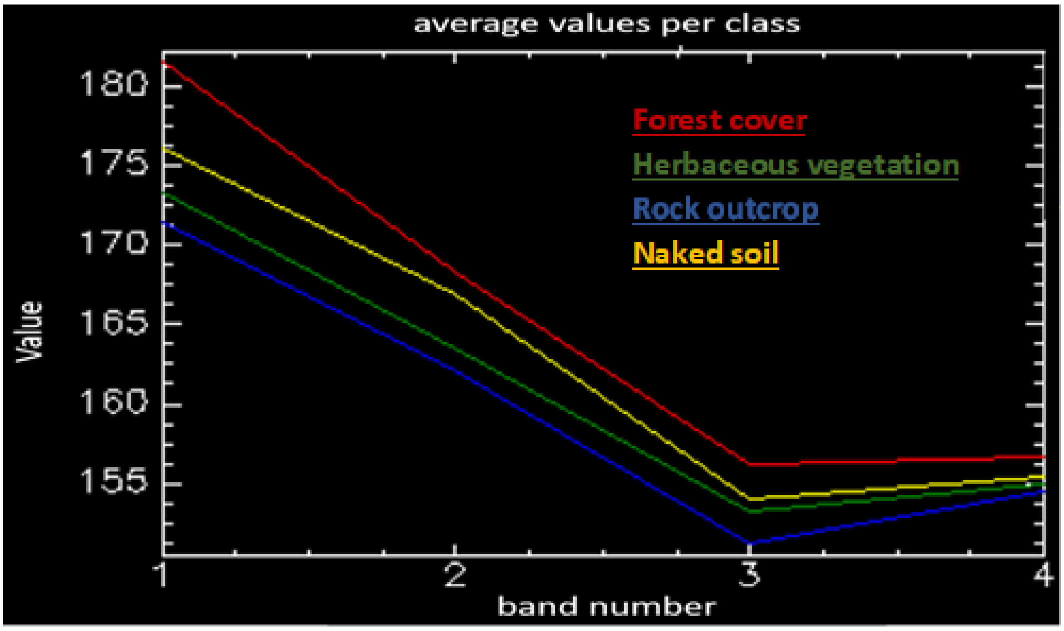

Fig. 7. *Results of the trained separation algorithm for the study area*

4. Conclusions

This study evaluated the photosynthetic activity of the *Polylepis* relict forest. The main findings of the study are the following:

1. Close-range photogrammetry allowed us to get high-resolution aerial photos, resulting in resolutions of the 4-band ortofotomosaic of 9 cm. Therefore, a successful analysis of an Andean forests was possible, including the calculation of vegetation index, and the generation of digital models needed in several types of analyses;
2. We found values in vegetation indexes (NDVI/EVI) ranging between 0.708 and -0.539 / 0.00059 and -0.00023, which stand for a major photosynthetic activity in the forest cover and in the herbaceous vegetation than rock outcrop and naked soil. Determination of thresholds (ranges) inside these indexes could contribute to the understanding of the conservation state of the forest;

3. The supervised classification helped to identify the area covered by the forest which could be updated regularly using similar studying approaches to determine its spatial dynamics. For the moment, the forested area accounted for 3.77% of the studied area;
4. We believe that the use of a methodology such as that presented herein, will contribute to the long-term monitoring of the high-value forests from the Andes Mountains, as well as to a better understanding of such forests dynamics in time. Also, these methods could be used to determine conservation state of natural space and to enable biomass calculations for studies of carbon sequestration in high Andean forests of Ecuador.

Acknowledgements

This paper was supported by the Interdisciplinary Doctoral School of the Transilvania University of Braşov. The authors would like also to thank to Escuela Superior Politécnica de Chimborazo for their technical and financial support and especially to all the research team of the Polylepis project. Finally, the authors would like to thank to the Environmental Ministry of Ecuador for allowing the authors to perform this study under Scientific Research Authorization No. 009-IC-DPACH-MAE-201.

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