ISSN 2953-6367
http://revistainvestigo.com

Julio - diciembre 2026
Vol. 7 No. 20, PP. 869-889
https://doi.org/10.56519/k6y27q77

EVALUACIÓN ESPACIOTEMPORAL DEL CRECIMIENTO DEL ABONO VERDE MEDIANTE TELEDETECCIÓN MULTIESPECTRAL CON UAV, SIG Y ANÁLISIS FISICOQUÍMICO DEL SUELO

SPATIOTEMPORAL ASSESSMENT OF GREEN MANURE GROWTH THROUGH MULTISPECTRAL UAV REMOTE SENSING, GIS AND SOIL PHYSICOCHEMICAL ANALYSIS

Hernán Eriberto Chamorro Sevilla[1], Rodrigo Ernesto Salazar López[2], Nanci Margarita Inca Chunata[3], Keylly Marcela Chávez Inca[4]

{hernan.chamorro@espoch.edu.ec[1], rodrigo.salazar@espoch.edu.ec[2], ninca@espoch.edu.ec[3], keylly.chavez@spoch.edu.ec[4]}

Fecha de recepción: 15/06/2026 / Fecha de aceptación: 06/07/2026 / Fecha de publicación: 08/07/2026

ABSTRACT: This study evaluated the spatiotemporal dynamics of a green manure mixture (Vicia sativa L. and Avena sativa L.) under high-Andean conditions using multispectral UAV remote sensing, GIS, and soil physicochemical analysis. Field experiments were conducted at an altitude of 2,850 m above sea level using DJI Mavic 3 Multispectral UAV. Data were collected in March and May 2026. Correlation analysis was performed between vegetation indices (NDVI, SAVI, and NDRE) and soil physicochemical properties, including pH, organic carbon, phosphorus, potassium, and soil texture. Laboratory analyses showed that the soil was slightly alkaline, with a sandy loam texture but low concentrations of organic carbon and available phosphorus. Multispectral imagery revealed a considerable increase in canopy vigor and biomass between the two monitoring dates. SAVI effectively minimized soil background effects during the early growth stage, whereas NDVI showed greater temporal variability associated with biomass development. In contrast, NDRE remained relatively stable, indicating a more uniform chlorophyll distribution and physiological condition of the crop. The integration of multispectral UAV imagery, GIS, and soil physicochemical analysis proved to be an effective approach for assessing the spatiotemporal development of green manure crops under high-Andean conditions. This integrated methodology enabled the identification of spatial variability in crop development associated with soil physicochemical properties, providing valuable information to support site-specific crop management and sustainable agricultural practices.

[1]Escuela Superior Politécnica de Chimborazo, Ecuador, https://orcid.org/0000-0002-8531-7116; +5930996487535
[2]Escuela Superior Politécnica de Chimborazo (ESPOCH) Sede Orellana, Ecuador, https://orcid.org/0000-0001-6194-1638; +593999444777
[3]Escuela Superior Politécnica de Chimborazo (ESPOCH, Ecuador, https://orcid.org/0000-0001-6703-0878; +5930984672267
[4]Escuela Superior Politécnica de Chimborazo (ESPOCH) Sede Orellana, Ecuador, https://orcid.org/0000-0003-0780-6704; +593998603125

Keywords: Precision agriculture, green manure, UAV remote sensing, vegetation indices, soil physicochemical analysis, Andean agriculture

INTRODUCCIÓN

Increased usage of sustainable agriculture has resulted in an increasing trend in practices that increase soil quality through reducing the reliance on chemical fertilizers and other external inputs. The use of green manures is among the most efficient means of replenishing soil fertility, nutrient provision, improving soil structure, and promoting sustainability. Incorporation of green manures into the process of agricultural production is known to provide for organic matter addition, improved soil aggregate formation, increased water infiltration and storage, and reduced soil erosion (1-4). Apart from improving the physical and chemical characteristics of soils, the use of green manures stimulates biological activity through creating conditions for microbes involved in nutrients mineralization and organic matter decomposition (1-4).

Leguminous green manures are of special importance due to the ability to develop symbiosis with nitrogen-fixing bacteria, allowing for incorporation of atmospheric nitrogen into the soil-plant system. Combining leguminous green manures with grass like oats (Avena sativa L.) results in greater efficiency of nutrient recycling, better protection of the soil surface, and maintenance of the proper C: N ratio during decomposition of the green manure materials (5-8).

However, the performance of the green manure crops shows considerable spatial variability across agricultural plots. The variability of soil parameters, such as its texture, organic matter content, nutrient status, moisture and others causes the uneven growth and biomass formation of the crops in distinct parts of agricultural fields. Traditional field evaluations are mostly based on biomass harvesting and observation; although such methods allow us to obtain valuable information about the state of crops, they are only certain parts of field conditions. These methods are labor and time-intensive, and they lack the spatial variability of crops at the field level especially during early growth stage (9–11).

Precision agriculture technologies including the remote sensing allow to significantly increase the accuracy of evaluation of crop condition by monitoring from above. Among remote sensing techniques, the use of UAVs with multispectral imaging sensors is becoming increasingly popular because of the important level of flexibility and resolution of the imagery provided by such equipment. In contrast to the satellite platforms, the use of UAVs allows the repetition of the observations under the favorable local weather conditions and provide the dataset that can be used for field-scale analysis and are appropriate for the short cycle crops and cover crops (12–15).

Multispectral imagery makes it possible to derive vegetation indices characterizing physiological status of crops because of spectral reflectance data. The Normalized Difference Vegetation Index (NDVI) is one of the most widely used spectral indices for estimating canopy vigor, biomass accumulation, and photosynthetic activity in agricultural systems and has shown reliable performance under heterogeneous environmental conditions, including high-Andean agroecosystems (3,22,25). The Normalized Difference Red Edge Index (NDRE) is more sensitive to variations in chlorophyll content and plant nutritional status, particularly after canopy closure, making it suitable for monitoring crop physiological condition in precision agriculture (23). Likewise, the Soil-Adjusted Vegetation Index (SAVI) minimizes the influence of exposed soil during the early stages of crop establishment, improving vegetation discrimination when vegetation cover is still incomplete (2,23). Previous studies conducted in Andean environments have demonstrated that the combined interpretation of NDVI, NDRE, and SAVI provides a more comprehensive assessment of crop development than the use of a single vegetation index by integrating information related to biomass production, physiological status, and soil background effects (22–25).

The value of vegetation indices increases considerably by incorporating these indicators into GIS systems. The ability to perform spatial analysis makes it possible to integrate vegetation maps with soil properties obtained in laboratory experiments, digital terrain models, and other environmental factors to reveal relationships between soil characteristics and spatial pattern of crop growth. This provides for creation of management zones, support of variable rate application in agriculture, and precision agriculture. Besides, the integration of multispectral imagery and physicochemical analysis of soils allows revealing how soil heterogeneity affects vegetation and crop development (21–24).

Whereas UAV-assisted remote sensing techniques have widely been investigated in commercial crops, fewer studies have looked at green manures grown under high altitude Andean environmental conditions. Fast growing species like common vetch (Vicia sativa L.) and oat (Avena sativa L.), which respond highly to changes in soil properties, serve well as model crops to assess the vegetation indices-soil properties interaction. The investigation into this interaction is necessary to enhance fertilizer application strategies, biomass production and sustainable agriculture.

This research project was intended to use UAV-assisted multispectral remote sensing data along with GIS and soil physicochemical property analysis to assess the spatiotemporal development of a green manure crop developed under Andean environmental conditions. The second aspect of the research was to assess the interaction between vegetation indices and soil properties.

MATERIALES Y MÉTODOS

2.1 Study area

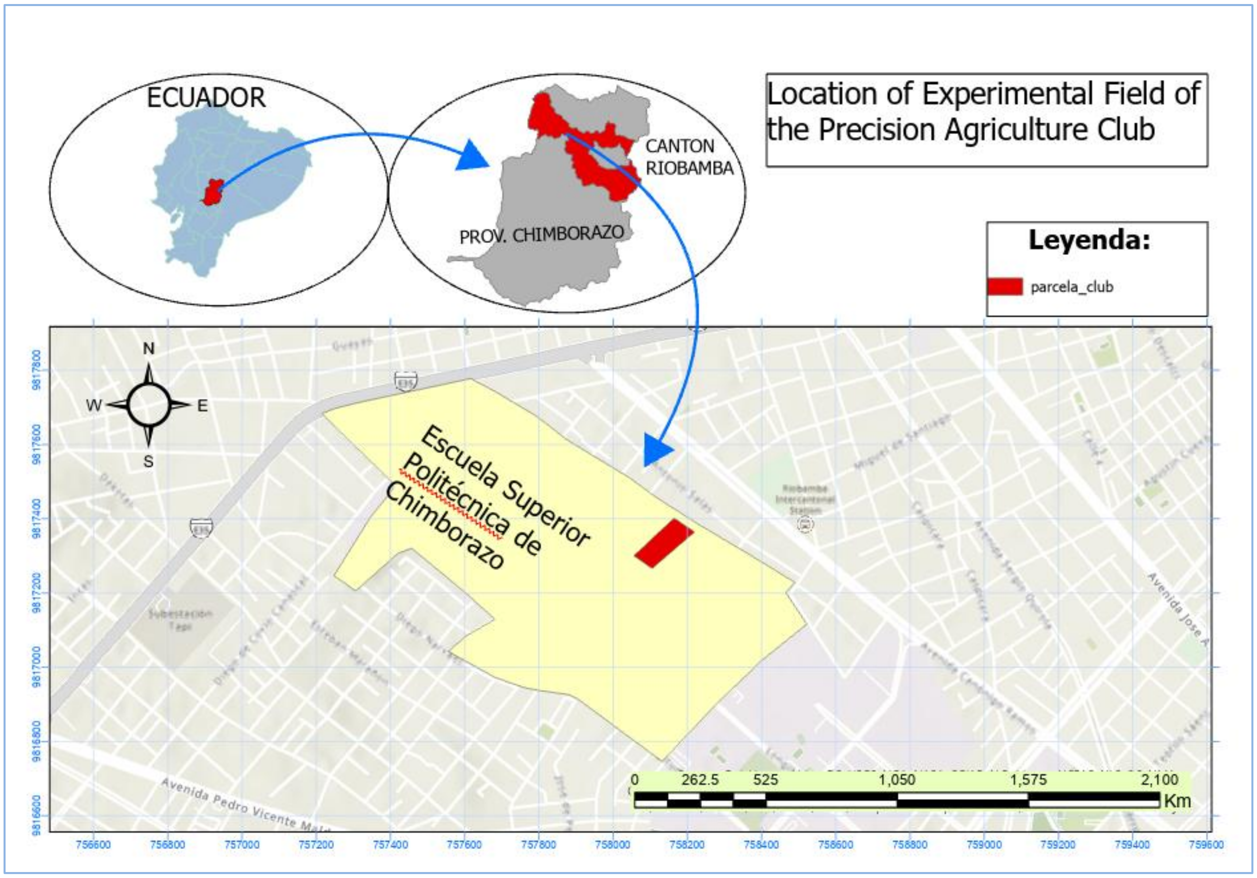

Figure 1. Location of the study area

The study was conducted at the experimental field of the Precision Agriculture Club, Faculty of Natural Resources, Escuela Superior Politécnica de Chimborazo (ESPOCH), which is situated at Riobamba, Province of Chimborazo, Ecuador. The experimental field covers an area of around 9,138.79 m² and is found at the Universal Transverse Mercator (UTM) coordinates 758134.34 E, 9817336.70 N (WGS 84, Zone 17S). Its average altitude is 2,850 m above sea level. The environment has an equatorial high-mountain, semi-humid mesothermal climate and has an average annual temperature of about 13.6 °C. It has high solar radiation and low nocturnal temperatures. All these characteristics are typical of the highland Andes of central Ecuador and make an ideal setting for evaluating the establishment and early growth of green manures in mountain agriculture.

The experimental planting consisted of a mixed seeding of common vetch (Vicia sativa L.) and oat (Avena sativa L.), shown on 6 February 2026. These crops were chosen because legumes fix nitrogen biologically and cereals produce rapid biomass growth and improve soil cover.

2.2 Soil Sampling and Laboratory Analyses

Soil sampling was performed prior to crop establishment as a means of assessing the first physicochemical conditions of the experimental field. Composite soil samples were taken using an established soil sampling protocol and were analyzed in the Soil Laboratory of the Faculty of Natural Resources, ESPOCH, using standard methods of soil analysis.

The variables analyzed included soil pH, electrical conductivity (EC), organic carbon, soil moisture content, available phosphorous (P), exchangeable potassium (K), soil bulk density, soil particle density, soil texture, and soil structure. The selection of the above-mentioned variables was based on the criteria that they are the most indicative of soil fertility and nutrient content, water retention ability, and physical characteristics affecting crop establishment.

Laboratory data was later integrated into a geospatial database for comparative analysis with soil variables and vegetation indexes obtained via multispectral UAV imagery.

2.3 UAV Data Acquisition and Image Processing

The monitoring of crops was done through a DJI 3 Multispectral (M3M RTK) UAV fitted with a multispectral camera and RTK positioning which ensures centimeter level accuracy in positioning during data acquisition. UAV flights were done twice during the establishment of the green manure crop on 21 March and 26 May 2026 allowing the evaluation of changes of development of the crop during time.

Vegetation indices were calculated from the multispectral bands acquired by the DJI Mavic 3 Multispectral sensor after radiometric calibration and orthomosaic generation. NDVI, SAVI, and NDRE were selected because they provide complementary information on canopy vigor, soil background effects, and crop physiological status during crop establishment. Table 1 summarizes the analytical equations and spectral bands used to calculate each vegetation index.

Table 1. Vegetation indices, analytical equations, and spectral bands used in this study

Vegetation index	Analytical equation	Spectral Bands (DJI Mavic 3 Multispectral)	Main application
NDVI	$\left(\frac{NIR - Red}{NIR + Red}\right)$	$NIR(840 \pm 26nm)/Red(650 \pm 16nm)$	Estimation of canopy vigor, biomass accumulation, and photosynthetic activity
SAVI	$\left(\frac{(NIR - Red)}{(NIR + Red + L)}(1 + L)\right)$ $where\ L = 0.5$	$NIR(840 \pm 26nm)/Red(650 \pm 16nm)$	Reduction of soil background influence during early crop development
NDRE	$\left(\frac{NIR - RedEdge}{NIR + RedEdge}\right)$	$NIR(840 \pm 26nm)/RedEdge(730 \pm 16nm)$	Assessment of chlorophyll content and crop physiological condition

The flight plan was programmed with the use of autonomous UAV flying software, and the flights were flown at the height of 40 m above ground level, 80% forward overlap, 70% side overlap and average ground speed of 6 m s^{-1}. This ensured sufficient image overlaps to allow accurate photogrammetric reconstruction while maintaining high spatial resolution appropriate for precision agriculture purposes.

Image processing was performed using Pix4Dmapper version 4.5.6. The image processing workflow implemented in Pix4Dmapper consisted of: (i) radiometric calibration using the DJI Mavic 3 Multispectral Reflectance Calibration Panel (CRP); (ii) initial image processing and automatic aerial triangulation; (iii) camera optimization; (iv) dense point cloud generation; (v) digital surface model (DSM) construction; (vi) multispectral orthomosaic generation for each spectral band; and (vii) export of calibrated reflectance orthomosaics as GeoTIFF files for subsequent analysis in ArcGIS Pro. During image acquisition, the integrated Sunshine Sensor was enabled to record real-time incident solar irradiance, allowing automatic correction of illumination variability between flight campaigns. Radiometric calibration converted the raw digital numbers into surface reflectance values, improving the radiometric consistency and comparability of the multispectral orthomosaics. Vegetation indices (NDVI, SAVI, and NDRE) were subsequently calculated in ArcGIS Pro using the Raster Calculator, and the resulting maps were integrated with the soil physicochemical data for spatial analysis.

2.4 Vegetation Indices

Three vegetation indices were used to find the development of crops throughout the entire monitoring period. NDVI index was used to measure the vigor of the plants, green biomass, and photosynthesis. The calculation of NDRE index allowed estimating the level of chlorophyll concentration and nutrient condition of the crop, especially when in advanced vegetative stage, since NDVI index can become saturated. SAVI index was considered for decreasing the influence of soil on the results of measurement and providing more exact estimation of plant performance with partial canopy coverage. The simultaneous use of these indices made it possible to conduct analysis of the physiological state of the crop, including measurements of biomass, chlorophyll content, and soil-adjusted vegetation index.

2.5 Spatial and Statistical Analysis

Spatial analyses were conducted using ArcGIS Pro software through the combination of vegetation indices maps and laboratory results of soil physicochemical properties. Thus, spatial variability of plant development was visualized and possible correlations between vegetation indices and soil characteristics could be found within the experimental field.

Descriptive statistical analysis was done using R. Mean value, minimum value, maximum value, standard deviation, quartile values, and coefficient of variation were calculated for each vegetation index and soil parameter. Boxplots and histograms were created to evaluate changes in distribution of vegetation indices over time between the two periods of observations. The combination of descriptive statistical analysis, spatial analysis, and laboratory data allows evaluating the effect of soil physicochemical properties on early development of green manure crops under precision agriculture conditions.

RESULTADOS

3.1 Soil Physic-Chemical Characterization

The physic-chemical characterization of the soil used in this experiment created an environmental benchmark which was needed to understand the multi-spectral responses of the green manure mixture during the course of the experiment. Analysis in the laboratory showed that the area under study had favorable environmental conditions for crop growth; however, variations in soil nutrient distribution may cause certain effects on the first vegetative growth. Combining laboratory analysis of the soil properties with UAV based multi-spectral data can help interpret the resulting spectra in relation to agriculture.

Table 2. Physicochemical properties of the experimental soil before green manure establishment.

Ident.	pH	CE (µS/cm)	C org. %	Humedad %	P (mg/L)	K (meq/100g)	D. Aparente	D. Real	Textura	Estructura
1	7.45 L. Alc	230 NS	0.6 B	11.8	39.42 A	0.99 A	1.5	2.6	Arena franca	Suelta
2	7.61 L. Alc	111.4 NS	0.4 B	12.0	40.11 A	0.88 A	1.4	2.5	Franco arenoso	Suelta
3	7.52 L. Alc	84.6 NS	0.4 B	12.1	35.36 A	0.85 A	1.3	2.5	Franco arenoso	Suelta
4	7.63 L. Alc	112.1 NS	0.2 B	7.8	38.72 A	0.92 A	1.4	2.6	Franco arenoso	Suelta
5	7.53 L. Alc	92.8 NS	0.2 B	9.2	42.43 A	0.87 A	1.4	2.5	Franco arenoso	Suelta
6	7.59 L. Alc	102.5 NS	0.2 B	9.0	40.23 A	0.90 A	1.3	2.5	Franco arenoso	Suelta

Código
L. Alc = Ligeramente alcalino NS = No salino A = Alto M = Medio B = Bajo

So, soil analysis provided information about slightly alkaline reaction of the soil together with very low levels of soil electrical conductivity, which proves that there were no such factors as soil acidity or salinity limiting the possibility of crop establishment. Since pH of the soil belongs to the range where legumes and cereals can develop, it allows concluding about the good nutrient status of the soil and microorganisms taking part in the decomposition of the organic matter. Likewise, low electrical conductivity values confirm that there are no salts limiting crop establishment via causing osmotic stress during seed germination or root growth. Therefore, spectral heterogeneity seen in the UAV images cannot be related to the effects of salinity but should be caused by natural differences in the state of soil fertility and crops.

As for the fertility parameters, organic carbon and available phosphorus are the major nutrient limitations of the experimental field. Organic carbon is important in terms of supporting soil structure, soil moisture, cation exchange capacity, and microorganisms, so its low level shows low availability of mineralizable organic matter able to provide nutrients at the stage of crop establishment. On the other hand, phosphorus is a principal element involved in root growth and energy transfer, so its low availability can explain the differences in crops' development seen while monitoring. Despite there being no nutrition-related problems detected in the experimental field, local phosphorus deficiency is probably responsible for the heterogeneous vegetation indices obtained after the first UAV flight.

Potassium in an exchangeable form occurred at higher levels in the research area. Potassium regulates stomata opening, activation of enzymes, transport of carbohydrates, and water-use efficiency, all of which have direct relations to vegetative development and physiology of the plant in general. Potassium presence might be one of the factors that helped crops grow despite moderate nutrient deficiency in organic carbon and phosphorus. It is possible that this nutrient balance led to vegetation growing stronger over second observations.

Besides, physical attributes of the soil were favorable for crop growth. Soil bulk density pointed to low compaction of soil and therefore good pore continuity for root system development and gas exchange. The same concerns particle density, which is consistent with mineral agricultural soils without any structural deterioration. These properties allow for unrestricted roots development and soil exploration as well as sufficient oxygen diffusion.

According to the results of the texture analysis, sandy loam and sandy clay loam soil classes prevailed in the experimental field. Such textural classes provide a good balance between drainage, aeration, and water retention, which means that the risks of waterlogging can be avoided but at the same time soil keeps enough moisture needed for successful crop establishment. Even though coarse soils have less capability to retain nutrients than clays, they allow for fast drainage and reduce runoff, providing favorable physical conditions for crop emergence. Therefore, the results of the textural analysis may explain the uniformity of the canopy coverage recorded during the second UAV survey.

Taking into account the interpretation of both chemical and physical properties of soils, it can be stated that crop establishment took place in such an environment that had no physical restrictions; thus, nutrient variability became the main condition that could produce spatial heterogeneity of vegetation development. This conclusion is rather important since it gives an agricultural explanation of the variability obtained through multispectral images. Low vegetation index values areas, therefore, may be associated with the nutrient availability in the area and not with poor physical soil conditions. It is clear that the results of laboratory analyses allow integrating remote sensing and laboratory measurements and making the interpretation of the spatial vegetation variability possible.

From the point of view of precision agriculture, the preliminary soil analyses provide the basic framework for the interpretation of further crop vigor, chlorophyll and canopy development changes. Thus, the laboratory results are not the independent part of the study but the linking element between soil fertility and multispectral imagery that allows interpreting vegetation indices as crop responses to the existing soil conditions.

The lab characterization forms the foundation for interpreting the evolution of spectra recorded over the monitoring period. While the physicochemical characterization describes the environmental conditions that prevailed during the growth of the crop, the vegetation indices determined by the UAV record the effects of those conditions on the crop at spatial and temporal levels. The following section evaluates the effects through the analysis of NDVI and SAVI, two vegetation indices that capture the effects of the environmental conditions during the establishment stage of the crop.

The physicochemical characterization revealed that the environmental conditions in the experimental field were suitable for growing the crop despite variations in nutrient availability. To understand the influence of these environmental conditions on the growth of the crop, an analysis of the temporal evolution of vegetation vigor was conducted using NDVI and SAVI.

3.2 Spatiotemporal dynamics of vegetation vigor (NDVI and SAVI)

Temporal analysis of vegetation vigor shows a significant improvement in crop growth due to the gradual growth of the green manure mixture at the beginning of the growing season. Both NDVI and SAVI show an increasing trend in the canopy vigor in March-May. At the same time, each of the indices considers a different aspect of crop growth, since NDVI reflects mainly the increment of photosynthetically active biomass, while SAVI gives a better insight into the growth of the crops during the period of their establishment due to the elimination of the impact of soil brightness on results.

The descriptive statistics provided in descriptive statistics prove the clear tendency of increase in the central tendency of the vegetation indices between the monitoring dates. The increase in the mean and median of vegetation indices proves the general growth of vegetation vigor for most of the pixels as the crop grows. This assumption can be additionally supported by the fact that the upper quartile increases as well, which means that the crops become more vigorous not only in the most productive regions but also in the intermediate ones.

Table 3. Descriptive statistics of NDVI and SAVI obtained from UAV imagery during March and May.

Archivo	N	Min	P5	Q1	Media	Mediana	Q3	P95	Max	SD	Var	CV	IQR	Skewness	Kurtosis
NDRE_marzo	17009885	-0.32836005	-0.12117555	-0.0953418	-0.05360267	-0.06623054	-0.02024023	0.05120434	0.29098934	0.05445725	0.00296559	-101.594284	0.07510157	0.89570534	0.49746084
NDRE_mayo	26071341	-1	-0.14666772	-0.09866217	-0.06041424	-0.06118282	-0.02301318	0.02873772	0.24901648	0.05442434	0.00296201	-90.08529	0.07564899	-0.4306316	8.78899
NDVI_marzo	17008668	-0.3640451	-0.03730676	0.01244339	0.16589265	0.09319449	0.302802	0.53956157	0.7521404	0.1891757	0.03578745	114.03501	0.2903586	0.8172493	-0.49090886
NDVI_mayo	26076688	-1	-0.13350135	0.03948374	0.18977341	0.20770788	0.34320015	0.47894907	0.71610475	0.19415243	0.03769517	102.3075	0.30371642	-0.27193904	-0.45283842
RGBmarzo21	41058761	0	0	0	49.556847	0	116	157	255	63.114162	3983.3975	127.35709	116	0.6709392	-1.2654378
RGBmayo26	62960436	0	0	0	45.691467	0	102	144	254	57.43033	3298.2424	125.69158	102	0.66321456	-1.1573777
SAVI_marzo	17008668	-0.5460605	-0.05595926	0.01866477	0.248778	0.13978937	0.4541953	0.8093298	1	0.28360417	0.08043133	113.9989	0.4355305	0.8147252	-0.50101733
SAVI_mayo	26076688	-1	-0.2002483	0.05922445	0.28478152	0.31155628	0.5147918	0.71841323	1	0.29055604	0.08442282	102.02771	0.45556733	-0.23841022	-0.69223094

Though sharing a common trajectory with respect to time, there were slight differences in the way the two indicators responded to vegetation development, as reflected in their respective statistical distributions. The NDVI indicator experienced a continual increase in both its mean and median values over time, implying continued increase for vegetation cover while showing the crops. This was accompanied by a decreasing coefficient of variation, signifying the uniformity of biomass production in the area as canopy closure progressed. This decrease in the relative variability implies that the portions where crop emergence lagged in March managed to develop their vigor to levels like those of the already developed areas by May.

3.3 Relationship between soil physicochemical properties and vegetation indices

To complement the descriptive analysis, Spearman's rank correlation coefficient was applied to evaluate the relationships between soil physicochemical properties and vegetation indices. This non-parametric approach was selected because of the limited sample size (n = 6), making it more appropriate than parametric correlation methods. This non-parametric approach was selected because of the limited sample size (n = 6), making it more appropriate than parametric correlation methods. A strong negative correlation was found between soil organic carbon and both NDVI and SAVI during the first monitoring campaign ($\rho = -0.926$, $p = 0.008$), indicating that areas with higher organic carbon content exhibited lower spectral responses during the early establishment stage of the green manure crop. Likewise, electrical conductivity showed a strong negative correlation with NDRE in March ($\rho = -0.829$, $p = 0.042$). No statistically significant relationships ($p > 0.05$) were detected between the remaining soil properties and the vegetation indices evaluated. These findings suggest that soil properties may have influenced spectral responses during the initial crop establishment stage. This relationship became less evident after canopy closure, when vegetation became more spatially homogeneous.

Table 4. Spearman correlation coefficients between soil physicochemical properties and vegetation indices.

Soil property	NDVI (March)	NDVI (May)	SAVI (March)	SAVI (May)	NDRE (March)	NDRE (May)
pH	0.486	0.200	0.486	0.200	0.029	-0.257
Conductivity	-0.371	0.371	-0.371	0.371	**-0.829***	0.600
Organic carbon	**-0.926***	0.123	**-0.926***	0.123	-0.617	0.463
Moisture	-0.600	0.029	-0.600	0.029	-0.029	0.086
Phosphorus	0.714	0.543	0.714	0.543	0.600	0.486
Potassium	-0.257	0.143	-0.257	0.143	-0.714	0.486

It would be easier to visualize the dynamics through box plots compared to descriptive statistics alone. For the first monitoring period, the interquartile range covered a wide array of vegetation states, signifying heterogeneity of the crop emergence and the presence of seedlings alongside sizable soil exposure. The relatively low value of the media, together with many data points below the first quartile, signify an early establishment phase where vegetation had not yet developed enough to cover the whole soil surface.

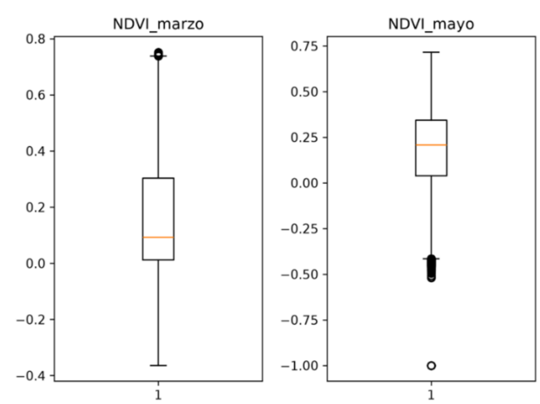

Figure 2. NDVI boxplots correspond to the March and May UAV surveys.

It should be noted that during the second monitoring session, the median value in the NDVI boxplot was increased, and the upper quartile also showed positive dynamics. This is explained by the continuous biomass growth at the monitoring site and the gradual increase in homogeneity of canopy cover of the experimental area. Even though there were still some small values on the plot, their amount significantly decreased which shows that most parts of the plot were able to develop vegetation. Decrease in the relative dispersion of NDVI values at the second monitoring session is also indicative of crop development becoming more even over time.

In addition, the NDVI histograms also confirm this conclusion. Thus, the histogram for March is characterized by high dispersion of low-positive values as well as a considerable number of pixels related to sparse vegetation and exposed soils. However, in May, the histogram showed the trend towards higher values with a significant decrease in the proportion of zero pixels.

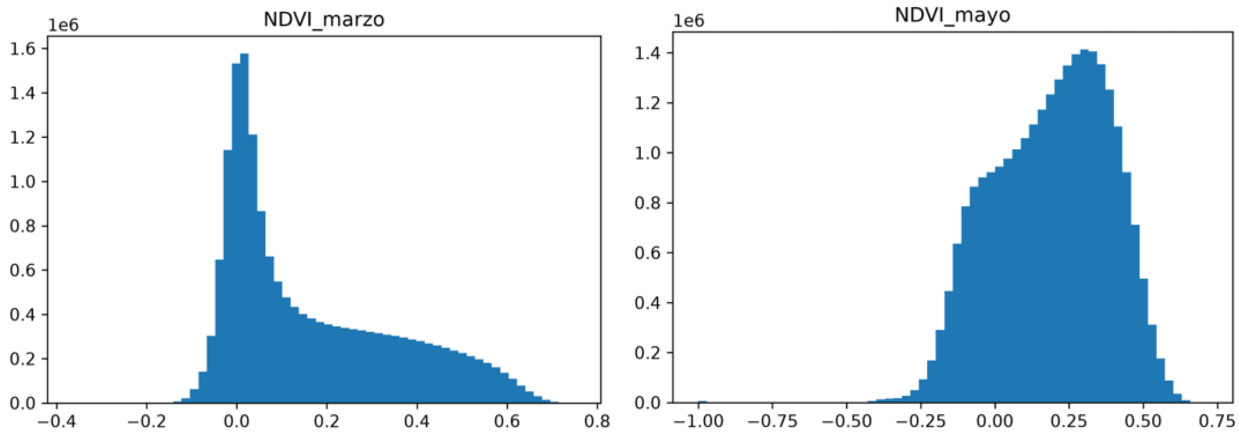

Figure 3. NDVI frequency distributions obtained during the two monitoring campaigns.

SAVI's temporal dynamics have shown behavior like the general trend in the study but provided additional information at an early stage of planting. Due to the existence of soil correction in SAVI, this indicator is less affected by the presence of exposed soil compared to NDVI in case of partial canopy cover. Such property becomes especially relevant for green manure crops at the stage of establishment, since there is still a significant part of exposed soil in this case between each plant. Therefore, it is expected that SAVI will provide a more correct estimate of vegetation vigor compared to NDVI.

According to the descriptive statistics, SAVI showed increasing trend from March to May, which is related to decreasing amount of exposed soil and increasing the area of crop canopy coverage. Like NDVI, the median and the upper quartile values moved to larger values, and relative variability decreased due to the better uniformity of distribution of vegetation on the field. The described trends indicate that in addition to growth of vegetation biomass, increase of vegetation vigor was caused by occupying exposed areas of the field by vegetation.

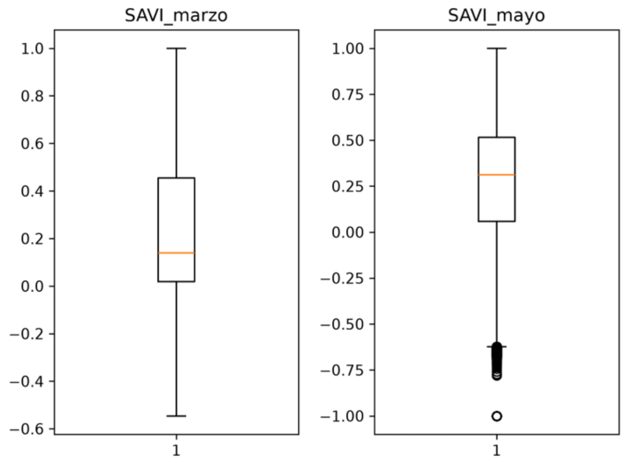

Figure 4. SAVI boxplots corresponding to the March and May UAV surveys.

The SAVI histograms validate these observations by showing a gradual movement of frequency of pixels towards the higher values of vegetation index in the second cycle of monitoring. In comparison to NDVI, March SAVI had lower occurrences of extremely low values due to the inclusion of soil adjustment factor that lessens the influence of soil spectrum. This makes SAVI more sensitive than NDVI when used to measure the development process of annual crops. However, in May, the distributions were similar, implying that the influence of soil exposure was reduced as the canopies closed.

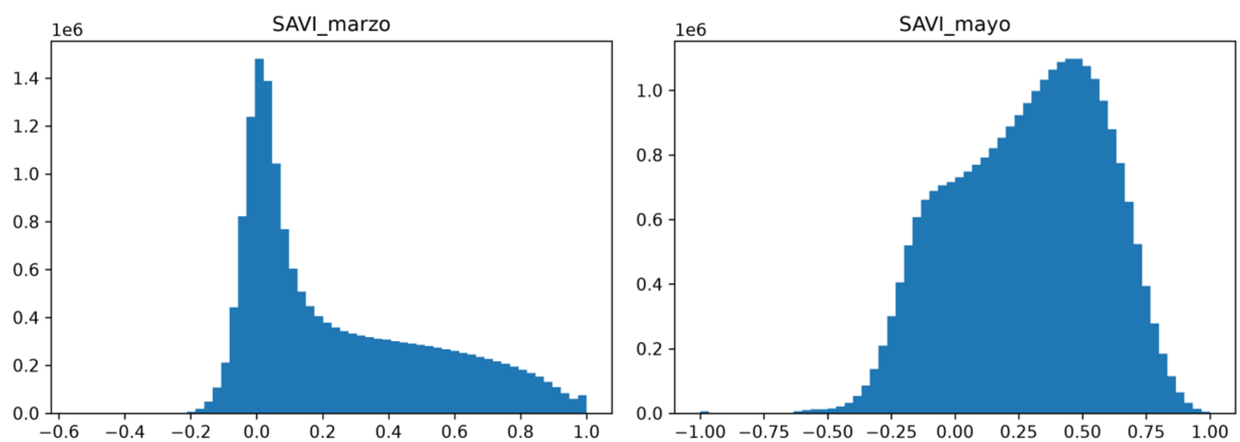

Figure 5. SAVI frequency distributions corresponding to March and May.

From the joint interpretation of NDVI and SAVI, the process of vegetation growth went ahead according to a unified temporal pattern, with an increase in biomass, closure of the canopy, and decreased spatial heterogeneity. The similarity of results from both indices shows successful crop establishment despite mild nutritional stress revealed during laboratory analysis. Initially, areas with smaller vegetation index values became like others in terms of field response, suggesting that good physical soil properties allowed for a uniform establishment of green manure mixture.

This conclusion is also supported by the laboratory characterization presented in the earlier section. The absence of physical soil limitations, as well as sufficient potassium content in the soils, might promote rapid growth of vegetation, while some variability in the contents of organic carbon and phosphorus could explain differences between field sites. Therefore, the temporal dynamics revealed by NDVI and SAVI represent the reaction of crops to both favorable soil structure and variable nutrients' availability in the experimental field.

However, NDVI and SAVI cannot give any information on the physiological state of plants. To get insight into the dynamics of chlorophyll content and nutritional condition of the canopy, the following section will analyze behavior of the Normalized Difference Red Edge Index (NDRE). This index is particularly sensitive to the variations in leaf chlorophyll content and physiological condition of plants.

3.4 Physiological response of the green manure crop in relation to NDRE

Whereas NDVI and SAVI provide descriptions of the temporal evolution of canopy development and biomass growth, NDRE can give a different aspect of the physiological state of the green manure crop. In contrast to traditional vegetation indices that use the red reflectance band, the NDRE includes the red edge band, which is especially sensitive to the variations in the chlorophyll content and biochemistry of leaves. Thus, this index allows evaluating the physiological state of vegetation with higher sensitivity during the intermediate and late phases of plant development when NDVI loses its sensitivity to more biomass due to canopy closure.

The results of descriptive statistics taken from descriptive statistics showed that NDRE had much lower variability compared to NDVI and SAVI indices. Although there were slight changes between the two campaigns, the overall variability was quite steady, showing a gradual development of the physiological state of vegetation while the canopy development occurred faster. This is in line with the natural course of development of the green manure mixtures where the fast vegetation coverage coincides with moderate changes in chlorophyll content.

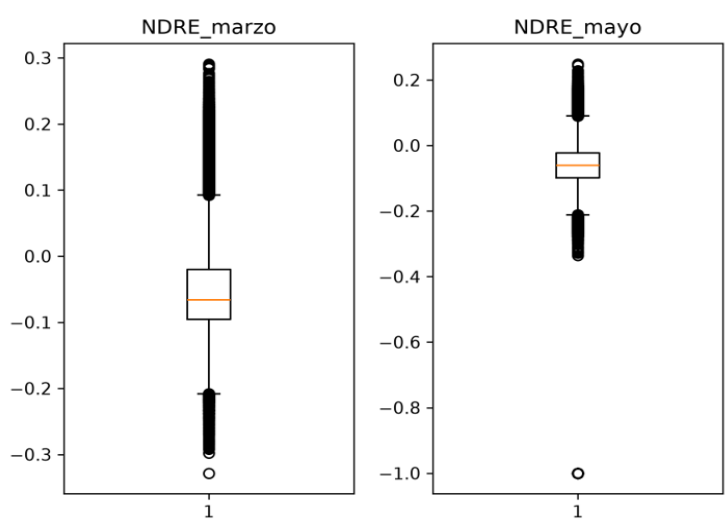

Figure 6. NDRE boxplots correspond to the March and May UAV surveys.

This tendency is clearly shown by the box-and-whiskers plot of NDRE, which shows that there were no significant changes in median and interquartile range between different monitoring dates. Unlike in NDVI, in which the biomass growth caused noticeable movement of the distribution upwards, NDRE changed little, suggesting that the amount of chlorophyll was evenly distributed on the experimental plot. This means that, after the seedlings became established, their physiological performance went ahead in a regular way regardless of soil variability.

Both surveys' interquartile ranges showed very minor variations, which suggests no momentous changes in variability of chlorophyll concentrations over the observation period. The lack of momentous change in upper quartiles suggests that there were no exaggerated physiological responses of the most vigorous sections compared to other sections of the experimental area. On the contrary, the development of the crop was rather consistent and even spatially in line with the homogenization of canopies that occurred according to the NDVI and SAVI analysis.

The histograms also provide some added confirmation of the above-stated conclusions. In March, the pixel frequency was evenly distributed on quite a narrow range around the median NDRE value, which is associated with the early physiological state of the crop after its establishment. In May, the histogram was more concentrated but kept the same central tendency. It is possible to assume that there were no momentous changes in chlorophyll concentration of the experimental field in spite of a considerable increase in biomass measured by NDVI and SAVI.

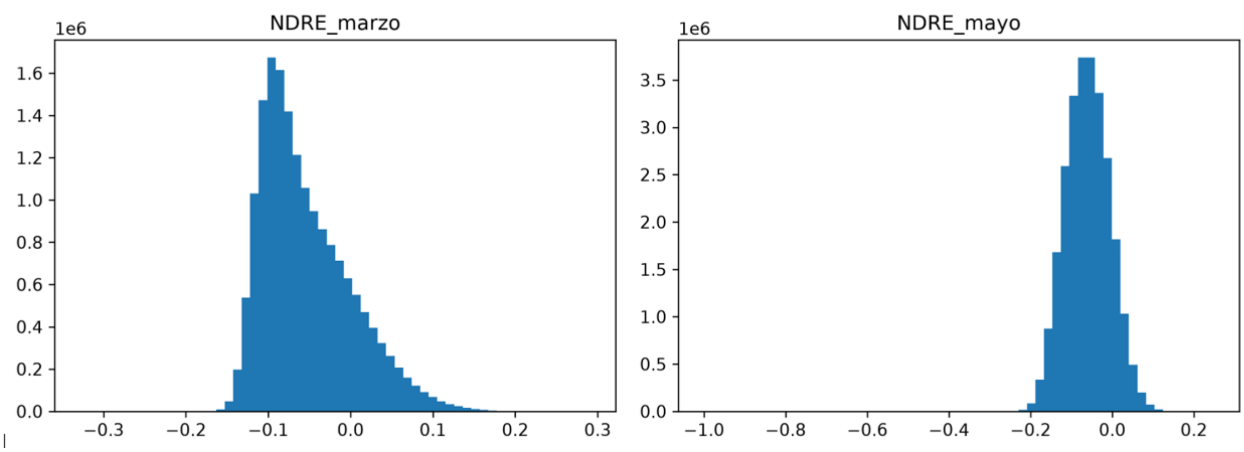

Figure 8. NDRE frequency distributions correspond to the March and May monitoring campaigns.

One of the features of NDRE response is the change in the symmetry of the distribution between different monitoring dates. Descriptive statistics show that the values of the skewness parameter became closer to symmetrical distribution in the case of the second UAV survey, which shows that the proportion of areas with reduced chlorophyll concentration decreased. In terms of agriculture, this trend means that the physiological heterogeneity of crops decreased with time, and almost all plants achieved the same physiological state by the end of the observation period.

The stable NDRE response cannot be regarded as the lack of development of crops because it means that the increase in biomass and canopy occurred faster than changes in chlorophyll concentration. Such a complementarity of responses explains the higher temporal differences in the behavior of NDVI and SAVI compared to NDRE because while NDVI and SAVI mainly accounted for changes in plant structures caused by growing vegetation cover, NDRE describes the stable photosynthetic apparatus. Thus, the three vegetation indices account for different but complementary aspects of crop development.

The physiological stability described by the NDRE response is also in line with the results of the laboratory study provided in Section 3.1. The lack of salinity stress and favorable physical characteristics of soils meant that no physiological stress appeared during the establishment of crops. Even though there were limitations due to the concentration of organic carbon and phosphorus, enough potassium and soil structure may support a constant level of chlorophyll concentration and photosynthesis.

With respect to precision farming, the combination of NDRE significantly improves crop monitoring because it provides physiological data which cannot be obtained based on biomass indices alone. Although NDVI and SAVI show areas where vegetation is growing, NDRE helps to decide if the plant material has the necessary physiological state. The interpretation of these indices minimizes the ambiguity which appears while estimating crop development using one spectral index and creates a solid foundation for defining the management zones requiring further investigation or different crop management practices.

Overall, the analysis of NDRE reveals that the physiology of the green manure mixture was rather uniform during the period of establishment of the green manure mixture, although there was some heterogeneity in the initial soil samples. Thus, this information, together with the structure data provided by NDVI and SAVI, confirms that the development of crops took place not only by accumulating biomass but also keeping the stable physiological status of most of the test field. Thus, the combination of the presented spectral responses allows making a comprehensive description of crop establishment in the Andean environment.

The combined interpretation of NDVI, SAVI and NDRE allows making the assessment of canopy development and its physiological state. However, the spectral information from the multispectral images should be supported by visual data. Therefore, the next section combines the RGB Ortho mosaics with the multispectral indices to assess the spatial dynamics of canopy coverage.

3.5 Interpretation of RGB Ortho mosaic images together with multispectral vegetation indices

The dynamic characteristics seen through the multispectral vegetation indices have been confirmed visually by the RGB Ortho mosaic images collected during the two UAV surveys. While the RGB Ortho mosaic images cannot provide any quantification of physiological variables or biomass production, they give the vital visual evidence needed to confirm the spatial patterns shown from the multispectral analysis. In simple terms, the use of RGB Ortho mosaic images alongside the NDVI, NDRE, and SAVI vegetation indices allows for a better understanding of crop growth by using both visual and spectral analyses.

Based on the Ortho mosaic image collected during the first survey; it can be noted that the crops were still in the establishment stage in March. There was no uniformity in vegetation coverage since there were many patches of bare soil present amidst the developing crops. This spatial heterogeneity is consistent with the statistical features of NDVI and SAVI, which show low medians and high interquartile because of the large variation in the vegetation coverage in March.

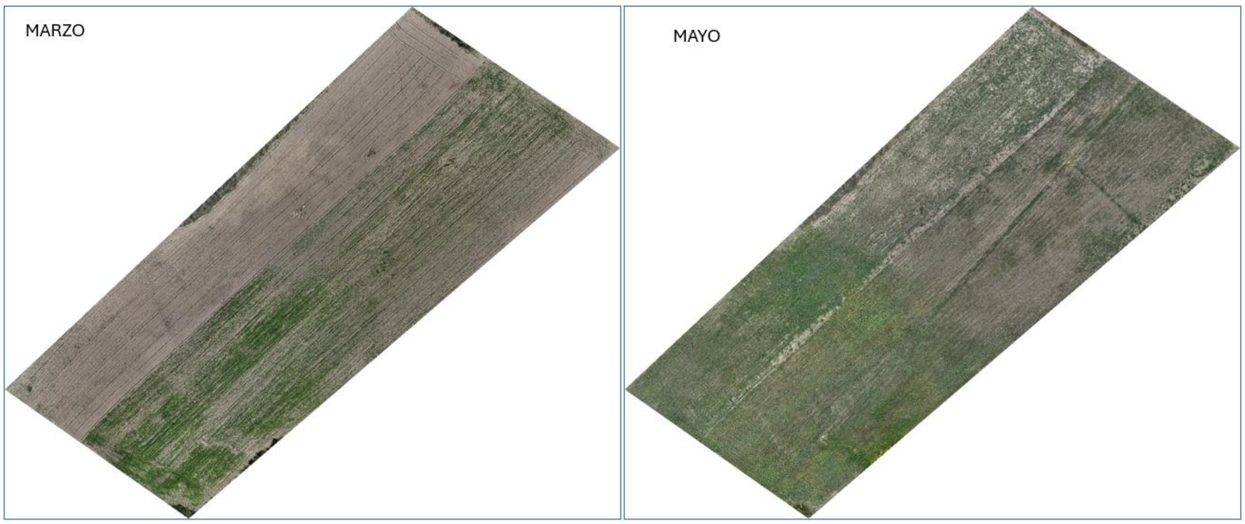

Figure 9. RGB Ortho mosaics acquired.

Secondly, it should be mentioned that there were clear differences in the visual aspect of the Ortho mosaics produced during the second period of monitoring. By May, the field was covered by more vegetation, hence, the higher density of the green canopy with fewer bare spots. This enhanced homogeneity of the green canopy is represented by a shift in the graphs of NDVI and SAVI towards higher values, hence, suggesting an overall growth for biomass rather than just the patches of vigorous vegetation. Therefore, the use of RGB Ortho mosaics can serve as visual evidence of the increased canopy closure due to biomass growth inferred from multispectral indices.

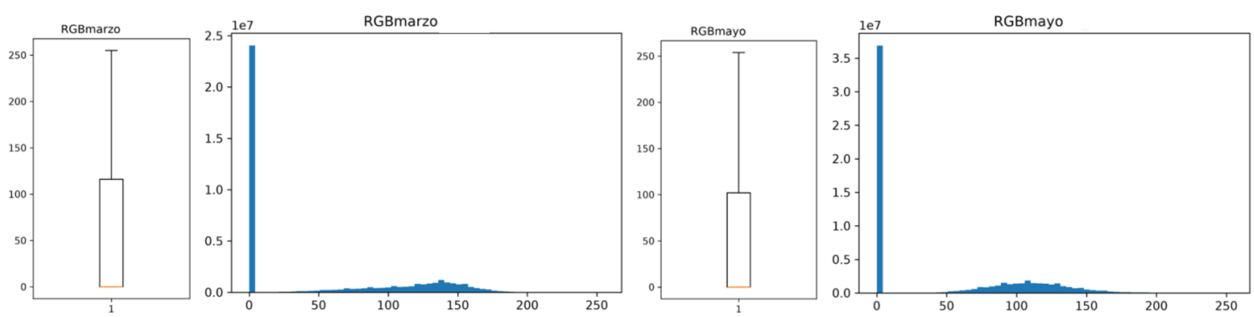

Figure 10. RGB Ortho mosaics obtained.

Also, descriptive statistics for RGB Ortho mosaics support the conclusion above. First, the interquartile range in the values of spectral response in visible channels became lower during the second period of monitoring, thus, suggesting that vegetation development had resulted in higher homogeneity of the visible signal. Secondly, the change in the histograms suggests that the variability of the surfaces with different reflectance properties (i.e., soil, crops, and young vegetation) has decreased. This conclusion is completely consistent with the changes in the values of NDVI and SAVI mentioned above.

Another benefit of using RGB Ortho mosaics is the potential of using this type of data in terms of easing interpretation of the spatial patterns of plant growth. Unlike vegetation indices that only provide a numerical value of the spectral response, RGB imagery can directly detect the spatial distribution of dense vegetation cover, sparse canopy, borders of the fields, and heterogeneous areas. Such visual information is especially helpful in interpretation of the multispectral product since this will help correlate any spectral anomalies with features in the field rather than interpret the statistical distribution only. In other words, RGB imagery adds more to the existing analysis of multispectral indices rather than substitutes it.

Combining RGB imagery with laboratory analysis of the soils reveals even more about the processes controlling the crop development. According to laboratory tests, soil physical properties were favorable for root growth and water flow, while variability in organic carbon and phosphorus was the main nutrient factor limiting crop growth. According to the RGB Ortho mosaic images, however, this nutrient variability did not prevent the crops from being proved on this field; instead, it may have affected the rate of canopy closure in some sectors. In March, when plants were showing, there were areas that developed their canopy slower than others; in May, this difference became much less pronounced.

Integrated interpretation of RGB imagery and the analysis of vegetation indexes illustrates the benefits of including other data in UAV-based scouting of crops. NDVI and SAVI measure structural changes associated with plant growth, while NDRE measures the physiological state of vegetation. Conversely, RGB Ortho mosaics offer a necessary context to ensure that any change in the values of vegetation indexes is caused by an actual change in the plant canopy and not by any spectral anomalies or errors in the image processing. A high degree of consistency across various data sources makes the interpretation of the process of crop growth much more dependable.

From a practical standpoint, the use of RGB and multispectral images serves as an example of one of the key benefits offered by the UAVs. A single flight of the UAV allowed obtaining regular Ortho mosaics suitable for visual analysis of the field as well as for obtaining multispectral information useful for assessing the physiological state of plants.

The combination of soil analysis in the laboratory, RGB Ortho mosaic images, and vegetation index analysis confirms that the green manure mixture was proved taking into consideration the physicochemical properties of the field. Positive canopy closure, increased plant vitality, and good physiological state confirm that the crop was positively affected by soil conditions in the field despite the somewhat uneven distribution of nutrients. It is worth noting that consistency between visual evaluation, descriptive statistics, and vegetation index analysis supports the validity of the methods used during the current study.

To conclude, the vegetation indices generated using the UAV imagery cannot be considered separately. A more holistic picture of crop growth appears when one analyzes laboratory soil test results, RGB Ortho mosaic images, and added vegetation indices. The results obtained have significance for further discussion based on earlier studies.

DISCUSIÓN

Combining soil analysis in the laboratory and remote sensing data collected using UAVs with multispectral cameras provided a complete understanding of the main parameters affecting the formation and early growth of the green manure mixture. At the same time, analyzing soil properties and spectral properties of the plants rather than only vegetation indices enabled naming the main parameters of plant growth during the monitoring period.

The laboratory soil analyses showed that the studied soil had good physical properties for plant cultivation because of low bulk density, low salinity level, and soil texture being sandy loam and sandy clay loam. In such soil, plants grow well because of proper soil aeration, no obstacles to water percolation, and easy penetration by roots. However, low levels of organic carbon and phosphorus made the soil nutrients quite heterogeneous throughout the experimental area. Such heterogeneity of soil nutrient content is likely to contribute to the spatial heterogeneity of plant spectral response at the initial stage of UAV monitoring when vegetation with low NDVI and SAVI values did not develop properly yet.

The contrasting behavior observed between NDVI and NDRE can be explained by the physiological sensitivity of each vegetation index during crop development. NDVI responded markedly to the increase in green biomass and canopy closure from March to May, reflecting the progressive accumulation of photosynthetically active vegetation. Similar responses have been reported in precision agriculture studies, where NDVI is considered highly effective for monitoring biomass accumulation during the early and intermediate growth stages of crops (3,4). In contrast, NDRE remained comparatively stable despite the substantial increase in biomass. This behavior is consistent with previous studies indicating that NDRE is more closely associated with chlorophyll concentration than with total biomass and becomes particularly useful after canopy closure, when NDVI tends to approach saturation under dense vegetation conditions (4,23). The relatively stable NDRE values observed in this study therefore suggest that, although biomass increased considerably during crop establishment, the physiological status and chlorophyll concentration of the green manure canopy remained relatively uniform across the experimental area. Similar responses have been reported for agricultural systems under high-Andean environmental conditions, where NDRE has proven to be a reliable indicator of plant physiological status despite significant structural changes in canopy development (22,24,25). Consequently, the complementary use of NDVI and NDRE provides a more comprehensive assessment of crop development, combining information on biomass production with physiological condition and reducing the limitations associated with the use of a single vegetation index.

On the contrary, changes of NDRE are quite small during the examined period despite the obvious increases of the vegetation biomass. It corresponds to the fact that red-edge region is physiologically sensitive to the chlorophyll concentration in the crops and not to the total amount of biomass. Thus, the stability of the NDRE can be interpreted as a relatively stable content of chlorophyll during the considered growth stage, whereas the main changes occurred via canopy closure and increasing vegetation coverage. The complementarity of the responses proves the effectiveness of using various vegetation indices for analysis of crop growth.

Although statistically significant correlations were identified for selected variables, the limited number of soil sampling points suggests that these relationships should be interpreted with caution. Nevertheless, the correlation analysis reinforces the descriptive patterns observed in the vegetation indices and highlights the importance of integrating soil physicochemical information with UAV-derived spectral data for crop monitoring under high-Andean conditions. Future studies including a larger number of sampling sites and repeated monitoring campaigns are recommended to validate these relationships.

It was especially helpful at the establishment stage since it reduced the impact of the exposed soil on the spectra, allowing vegetation to be seen more easily when there is an incomplete canopy closure. In the first survey, soil background had a significant contribution to the variability in the spectral characteristics while, in the second one, there was a gradual decrease of this influence due to the increase in vegetation cover. Therefore, the use of NDVI and SAVI together provided a more precise assessment of crop development than the separate use of any of these indexes, particularly in those areas where there is no complete closure of the canopy.

The RGB Ortho mosaic images could be considered a qualitative proof of the temporal trends found in multispectral analyses. Though the RGB images do not provide quantitative measurements of vegetation health, the reduction of exposed soil and the increase in the greenness of the canopy were consistent with the trends found in the spectral indexes. Thus, this agreement of qualitative and quantitative data proves that the remote sensing technique applied in this research is dependable.

About precision agriculture, the main innovation brought about by this study is its ability to show that using UAV multispectral imagery allows one to precisely describe the space-time dynamics of showing green manure cover crops as well as the effects of soil physicochemical heterogeneity on their growth. It should be noted that remote sensing is not intended to replace the laboratory soil analysis but rather supplement it through analyzing the whole field experiment plot and therefore making zoning and site-specific agronomy possible. Hence, the use of UAV imagery along with GIS and soil laboratory data seems like an effective way to check cover crops and implement sustainable soil management in Andean agriculture.

Furthermore, this research proves the effectiveness of UAV monitoring during the establishing period. It would be helpful to have more information on biomass, chlorophyll content, nutrients absorption, and Mult seasonal studies since this will allow one to interpret the spectral response of the crop under different environmental conditions. In addition, the use of machine learning techniques applied to multispectral imagery and soil data can improve precision agriculture algorithms.

CONCLUSIONES

From the results shown above, it is evident that the use of soil physicochemical analysis in the lab, multispectral images captured by the use of an unmanned aerial vehicle and GIS form a powerful framework when used together in assessing the development of green manure crops in the Andean environment.

From the preliminary results obtained from the laboratory analysis of the soil, it was clear that the physical characteristics of the soil in the experimental site were favorable for the establishment of crops since they had low salinity levels, good soil structure and texture. While organic carbon and available phosphorus in the soil were relatively low and hence could be considered as some nutritional constraints to the growth of crops, it did not hinder the successful establishment of crops.

Based on the above findings, it is clear that a combination of laboratory soil physicochemical characterization, multispectral UAV imaging, and geographic information system is an efficient way to track the growth of the green manure crop in the Andean environment.

With respect to the laboratory soil characterization, it was found that the field had favorable physical properties conducive to plant growth, based on low levels of salinity, proper soil structure, and proper soil texture. However, organic carbon and available phosphorus were relatively low, possibly inhibiting nutrient availability.

REFERENCIAS BIBLIOGRÁFICAS

1. Rouse JW Jr, Haas RH, Schell JA, Deering DW. Monitoring vegetation systems in the Great Plains with ERTS. In: Third Earth Resources Technology Satellite-1 Symposium. Washington (DC): NASA; 1974. p. 309-317.
2. Huete AR. A soil-adjusted vegetation index (SAVI). Remote Sens Environ. 1988;25(3):295-309. doi:10.1016/0034-4257(88)90106-X.
3. Tucker CJ. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens Environ. 1979;8(2):127-150.
4. Hunt ER Jr, Daughtry CST. What good are unmanned aircraft systems for agricultural remote sensing and precision agriculture? Int J Remote Sens. 2018;39(15-16):5345-5376.
5. Zhang C, Kovacs JM. The application of small unmanned aerial systems for precision agriculture: A review. Precis Agric. 2012;13(6):693-712. doi:10.1007/s11119-012-9274-5.
6. Colomina I, Molina P. Unmanned aerial systems for photogrammetry and remote sensing: A review. ISPRS J Photogramm Remote Sens. 2014;92:79-97.
7. Berni JAJ, Zarco-Tejada PJ, Suarez L, Fereres E. Thermal and narrowband multispectral remote sensing for vegetation monitoring from an unmanned aerial vehicle. IEEE Trans Geosci Remote Sens. 2009;47(3):722-738.
8. Mulla DJ. Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. Biosyst Eng. 2013;114(4):358-371.

9. Zhang H, Wang Y. A review of the application of UAV multispectral remote sensing technology in precision agriculture. Smart Agric Technol. 2025;12:101406.
10. Grbović Ž, Ivošević B, Budjen M, Waqar R, Pajević N, Ljubičić N, et al. Integrating UAV multispectral imaging and proximal sensing for high-precision cereal crop monitoring. PLoS One. 2025;20(5):e0322712.
11. FAO. Conservation Agriculture. Rome: Food and Agriculture Organization of the United Nations; 2021.
12. Lal R. Soil carbon sequestration impacts on global climate change and food security. Science. 2004;304(5677):1623-1627.
13. Brady NC, Weil RR. The Nature and Properties of Soils. 15th ed. Upper Saddle River (NJ): Pearson; 2017.
14. Doran JW, Parkin TB. Defining and assessing soil quality. In: Doran JW, Coleman DC, Bezdicek DF, Stewart BA, editors. Defining Soil Quality for a Sustainable Environment. Madison (WI): SSSA; 1994. p. 3-21.
15. Blanco-Canqui H, Lal R. Principles of Soil Conservation and Management. Dordrecht: Springer; 2008.
16. Fageria NK. The Use of Nutrients in Crop Plants. Boca Raton (FL): CRC Press; 2009.
17. Precision Agriculture Committee. Precision agriculture: Definition and concepts. Madison (WI): ASA; 2019.
18. Gebbers R, Adamchuk VI. Precision agriculture and food security. Science. 2010;327(5967):828-831.
19. McBratney A, Whelan B, Ancev T, Bouma J. Future directions of precision agriculture. Precis Agric. 2005;6:7-23.
20. Bongiovanni R, Lowenberg-Deboer J. Precision agriculture and sustainability. Precis Agric. 2004;5:359-387.
21. Cambardella CA, Karlen DL. Spatial analysis of soil fertility parameters. Precis Agric. 1999;1:5-14.
22. Leta Morocho PV. Correlación espacial de índice de vegetación de diferencia normalizada (NDVI) entre plataformas satelitales y vehículos aéreos no tripulados (UAV), en los agroecosistemas de cuatro cuencas de los altos Andes del macizo del Cajas (tesis). Cuenca: Universidad Católica de Cuenca; 2023.
23. Vera-Esmeraldas A, et al. UAV-Based Spectral and Thermal Indices in Precision Agriculture. *Agronomy*. 2025;15(11):2569.
24. Jara C, et al. Study of wetlands in the Ecuadorian Andes through comparison of Landsat-8 and Sentinel-2 imagery. *Revista de Teledetección*. 2019.
25. Zea P, et al. NDVI Performance for Monitoring Agricultural Energy Inputs in the Ecuadorian Andean Region. 2025.