USE OF UAV BASED VEGETATION INDICES FOR MAPPING AND MONITORING OF PLANT HEALTH IN VIETNAM'S COFFEE PLANTATIONS

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ABSTRACT: High spatial and temporal resolution images obtained with Unmanned Aerial Vehicles (UAVs) provide valuable information for precision agriculture. In addition to map various surface features, accurately delineate farm boundaries, identify and count individual trees, multispectral UAV-images are increasingly analyzed for species differentiation and crop dynamics monitoring. The objective of this study was to develop a practical methodology to use vegetation indices (VIs) derived from UAV-images for mapping and monitoring of plant health in Vietnam's coffee plantations. This study was conducted with UAV aerial photography using MicaSence red-edge multispectral sensor in four flight missions in seven locations of Robusta and Arabica coffee plantation in Lam Dong province during the 2020-2021 season. Different VIs, including Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge (NDRE) and Leaf Chlorophyll Index (LCI), were computed and compared with coffee leaves' chlorophyll contents measured by the SPAD-502 Chlorophyll Meter during ground truthing. The observed high correlations between VIs and SPAD readings suggested the significance of VIs for plant health/nutrient monitoring. Based on these empirical analyses, NDVI and NDRE were then selected to develop scoring parameters for plant health/nutrient mapping and monitoring. With integrated geospatial analytics, 558 smallholder coffee farms were mapped/ranked in terms of general plant health and spatially monitored 4 times during one crop cycle for nutrient level and early detection of plant stress such as nutrient deficiencies, water stress, pest or disease attacks. The results of this study showed that the streamlined use of UAV-based VIs, especially NDRE scores in an integrated system for farm monitoring can be established and used in other coffee plantation areas.

1. INTRODUCTION

Vietnam is the second largest coffee producer in the world after Brazil with Robusta coffee accounting to 97 per cent of Vietnam's total output (FAO, 2014). Coffee production, mostly in scattered smallholder farms, has been a major source of income for about a million families who mostly inhabit hilly areas in Central Highland and North-western provinces. In practice, cultivation of smallholder coffee plantation is done using traditional or conventional techniques, where farm practices and the level of farm inputs are based mostly on conventional farm monitoring methods, e.g., through labor-intensive scouting, destructive field sampling, and costly laboratory assays. Day-to-day farming works such as manual weed clearance, plant trimming, manual watering, blanket pesticide spraying and fertilizing are varying from farm to farm due to farmers' experience and discretion, hence usually not in accordance with the sustainable agriculture principles. This calls for advanced non-destructive monitoring technologies in providing accurate farm information for effective on-farm management of coffee plantations that help increase farmers' control and localized applications with minimization of resource usage, and thus improve the crop yield and farm profitability.

Satellite remote sensing have long been applied for crop mapping and monitoring in large scale due to its spatial and temporal coverage but often hindered by frequent cloud cover in tropical areas. Small unmanned aerial vehicles (UAV) have emerged in recent years as a versatile remote sensing platform used by scientists and agricultural producers for collecting data at very high spatial and temporal resolutions. Specifically, with low-attitude and flexible flight operations, UAVs can play an important role in monitoring smallholder agricultural systems (e.g., coffee farms), where persistent cloud cover often hinders optical remote sensing systems in acquiring quality images. UAV remote sensing can map various surface features, delineate farm boundaries and identify different crops, while repeated images of critical crop growth stages can be obtained and analyzed to monitor crop dynamics. Equipped with RGB, multispectral or thermal cameras, UAVs can provide precisely-timed, fine-grained data for different-purpose land mapping and crop health monitoring.

Previous studies indicated that early detection of coffee plant health conditions can assist in immediate, appropriate and effective remedial actions. In addition to the plant biophysical parameters such as plant height, crown shape/size, vegetation volume, Leaf Area Index (LAI), etc., plant health condition can be effectively monitored by remotely sensed vegetation indices (VIs). In remote sensing based plant studies, Normalized Difference Vegetation Index (NDVI) has been used widely in vegetation mapping and in differentiating healthy and stressed vegetation, providing early warning with regards to the condition of crops before becoming evident to the human eye (Bhagat *et al.*, 2020). Recently, there has been an increased interest in the use of red-edge bands (between red and near-infrared spectra) in vegetation analysis as an effective indicator of chlorophyll content in vegetation. Overcoming 'saturation' limitation of NDVI in dense vegetated areas, red-edge VIs are sensitive to small changes in canopy foliage content, gap fractions and senescence (while NDVI has low sensitivity). And as chlorophyll levels in leaves are closely related to the nitrogen status in the plants (Netto *et al.*, 2005), the red-edge VIs are successfully used in numerous empirical research to detect and monitor nitrogen (nutrient) deficiencies in crops, especially for perennial crops such as coffee plantations (Dunn *et al.*, 2017). Moreover, detecting coffee plant health at early stage together with creating timely plant health maps can help growers in quickly identifying intra-field variability for informing spatially variable management responses to plant stress that will maximize yield (Katsuhama *et al.*, 2018). So far, very few studies have investigated the potential of using red-edge VIs from the UAV data for coffee plants chlorophyll or nitrogen concentration estimation. This paper focuses on (1) identifying appropriate vegetation indices obtained from UAV images in estimating critical levels of chlorophyll or nitrogen concentration in Robusta and Arabica coffee plants; (2) determining practical VI-based scoring parameters for coffee farm health monitoring; and (3) monitoring of coffee crop health stress in the UAV-surveyed Robusta and Arabica coffee plantations over one year of crop calendar.

3. MATERIALS AND METHODS

3.1 Study Area

The experimental studies were conducted at seven different locations (Area of Interest or AOI) in Lam Dong province – second largest coffee production area in Vietnam - during 2020-2021 growing season (Figure 1 and Table 1).

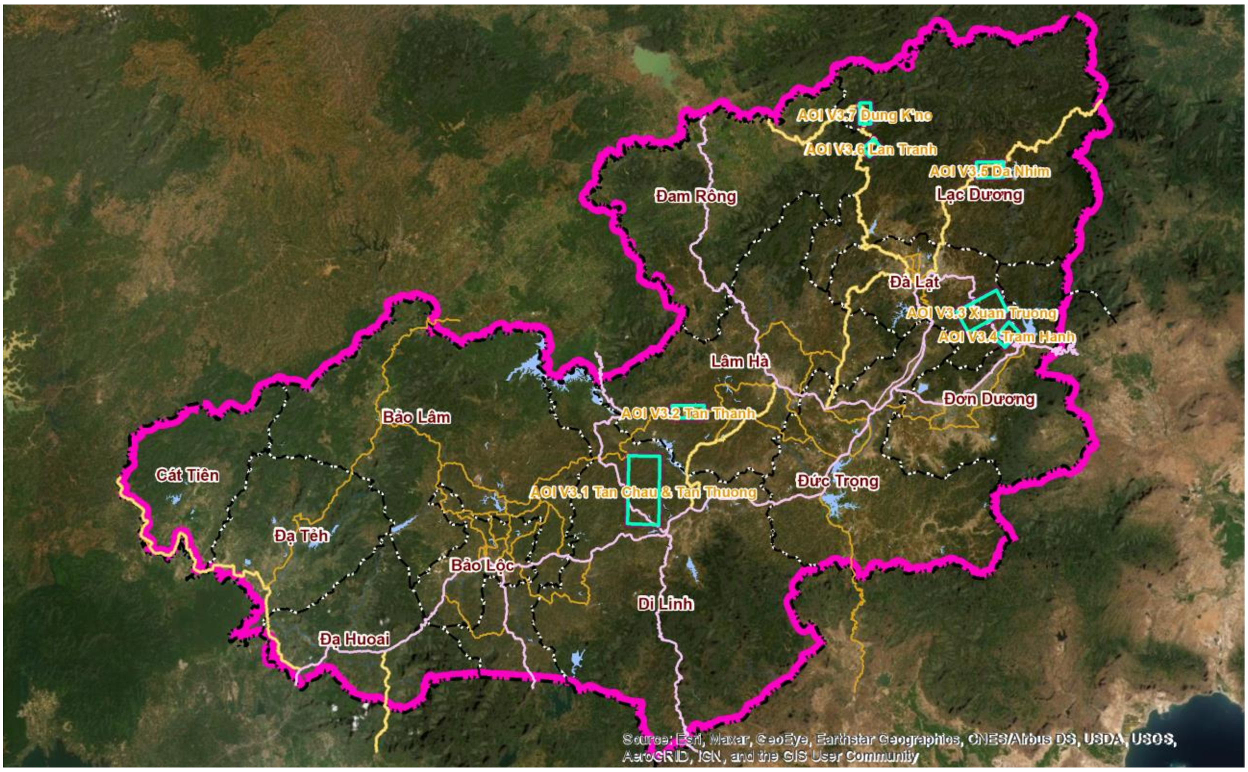


Figure 1. Study area map of seven AOIs with coffee plantations in Lam Dong province

The study area features hilly terrain with average elevation (above mean sea level) ranging from 1,000m (Di Linh highlands) to 1,500m (Da Lat city) and 1,600m (Lac Duong district), with the average slope ranging from 5-15^0 in Di Linh highlands to 10-30^0 in Da Lat and Lac Duong sub-areas and reaching 30-40^0 on some high-hills. With varying elevation, the area has favorable climate conditions for Arabica (in Lac Duong, Da Lat city) and Robusta (Bao Loc, Di Linh, Lam Ha districts) coffee plantations - average rainfall around 1,400-2,200 mm/year, short three-month dry season and mean annual temperature of 15-20^{0}C. The area is predominantly covered by fertile brown or red-yellow basaltic soils with some patches of faded gray soils. With favorable soil and climate conditions, the area is intensively cultivated with varieties of Robusta and Arabica coffee in smallholder coffee farms of 0.4 – 3 ha in size. With the increase in global market requirements on sustainable coffee certification, farmers are encouraged to improve their compliance with environmental sustainability standards. According to certification auditors, problems such as nutrient deficiency, low quality seedlings, weed infestations, water stress and pest or disease attacks are occurring within the study area calling for better farm monitoring and timely advice on improved practices, such as necessary pest and disease controls as well as nutrient application.

Table 1. Coffee plantations mapped by UAV aerial photography in seven AOIs in Lam Dong province

Locations (AOI)	Address	Elevation (m)	Coffee species	UAV mapping area (ha)	Coffee plantation area (ha)	Number of coffee farms
AOI V3.1	Tan Chau and Tan Thuong communes, Di Linh district	950 - 1000	Robusta	840	278	209
AOI V3.2	Tan Thanh commune, Lam Ha district	1000	Robusta	270	96	51
AOI V3.3	Xuan Truong commune, Da Lat city	1500	Arabica	520	81	117
AOI V3.4	Tram Hanh commune, Da Lat city	1500	Arabica	275	39	43
AOI V3.5	Da Nhim commune, Lac Duong district	1600	Arabica	215	33	72
AOI V3.6	Lan Tranh village, Dung Kno commune, Lac Duong district	1600	Arabica	140	25	35
AOI V3.7	Cluster 1&2, Dung K'no commune, Lac Duong district	1600	Arabica	150	14	30

3.2 Multispectral Image Acquisition and Processing

Multispectral UAV aerial photography was conducted repeatedly in 4 missions during the 2020-2021 coffee season, e.g., in July, September, December 2020 and March 2021 (due to certain circumstances, the study could not start in March 2020 as planned). A VTOL WingtraOne UAV mounted with MicaSense RedEdge-MX camera was used in the aerial photo collections with multispectral reflectance calibrated on the field before each of flights. Trimble X2 equipment with RTK GPS was used for accurate GCPs marking. A total of 30 50-minute flights at 147m altitude in each of four flight missions were flown and yielded high-quality multispectral aerial photos with 70x70% overlap and 10cm Ground Sample Distance (GSD). The UAV aerial mapping surveys were conducted with high standards to ensure quality and high accuracy of aerial mapping (see Pham Xuan Hoan *et al.*, 2021 for more details).

Acquired multispectral image sets from each of four UAV flight missions were processed in Pix4Dmapper 4.6, where all overlapped images from each of 7 mapped AOIs were aligned, tie-points identified and stitched together (georeferened and mosaicked) to build multispectral ortho-rectified images of the whole area of each locations. With 92 high-quality GCP markers, the spatial accuracy of an outputted reconstructed images ranges between 10-15cm ensuring for high accuracy of smallholder coffee farm mapping. Then, the ortho-mosaicked images were radiometrically calibrated using the Radiometric Calibration Model in MicaSense Atlas software. The calibrated reflectance orthomosaics were derived for each of AOIs including 5 bands (e.g., blue, green, red, red-edge and NIR) with 10cm pixel resolution, in WGS84/UTM zone 48N coordinate system and packaged in GeoTIFF format. The final outputs of UAV image processing for each of seven mapped locations in each of four flight missions include: (1) multispectral 5-band ortho-images, (2) point clouds, and (3) DSMs.

3.3 Ground Truthing and Field Measurement

Alongside with UAV aerial survey, ground truthing works with field inspections and farm information collection were conducted in each of four missions to support image interpretation and analysis. The sampling of coffee farms for representative ground truthing in each of 7 AOIs was based on visual stratification of delineated coffee farms supported by UAV-acquired RGB composite or NDVI index maps and location maps. Equipped with a Nikon AW130 camera with built-in GPS and mobile maps, coffee farms were sampled in each of AOIs and on-field inspected for plant volume, growth and health conditions, recorded with geo-tagged ground photos, farm locations and related information.

In addition, a Minolta SPAD-502 chlorophyll meter was used for direct-leaf measurement of chlorophyll concentration in coffee trees as an indirect indicator for tree growth - nutrient (nitrogen) status of coffee trees. Guided by NDVI index maps and visual inspections, mature coffee trees were selected within sampled farm plots based on representation of intra-plot variability and tree health states for SPAD readings. Trees with different health states (Arabica or Robusta coffee species, healthy leaves, yellowish or brown leaves) and with different disease symptoms (e.g., leaf rust, mole infections) were selected for experimental SPAD readings. Following previous researches (e.g., Netto *et al.*, 2005), the SPAD readings were measured and recorded for each of selected (and geo-tagged) coffee trees, including at least four leaves in four directions (e.g., a second to fourth leaf pair on a plagiotropic branch counting from the apex). Coded and geo-tagged (by GPS photo) SPAD readings were averaged for each of the measured trees for comparative and correlation analysis with UAV-derived VIs for tree crown-level and farm-level assessments as shown below. Based on the recorded SPAD readings with careful field inspections of coffee plants under severe stress, the upper threshold values of SPAD readings (representing coffee plants with clear visible nutrient stress symptoms) were defined as SPAD_TB = 43(±5) for Robusta and SPAD_TB = 48(±5) for Arabica coffee plants (Figure 3).

Figure 2. Robusta plant in AOI V3.2 with nematodes infection (SPAD readings = 37)

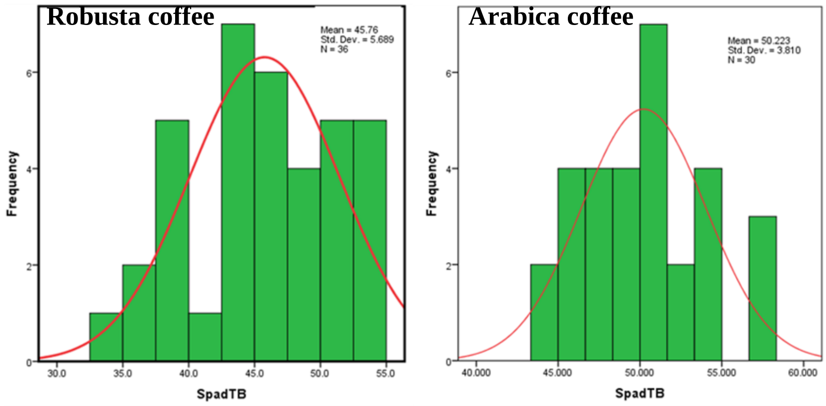


Figure 3. SPAD readings threshold values of nutrient deficiencies for Robusta and Arabica coffee trees

3.4 Image Analysis for Coffee Farm Mapping

Using processed ortho-images and index maps acquired in July 2020, smallholder coffee farms in seven locations were mapped, including: (1) farm boundaries delineation with ArcGIS and verified by farm visits with GPS and/or authenticated by farm owners; (2) differentiation of vegetation and non-vegetation portion of each coffee farm by NDVI thresholding and calculation of vegetation fraction (VF) in ArcGIS; (3) weed mapping and shade tree mapping with eCognition segmentation and point-cloud classification of canopy heights; and (4) coffee tree recognition (crowns) and counting with eCognition template matching (Figure 4).

The mapped coffee farms with individual coffee tree crowns and associated information were coded and integrated into a GIS farm database in ArcGIS for further processing and analysis of coffee farm and coffee tree health conditions.

Figure 4. Delineated coffee farm with mapped tree crowns

3.4 Vegetation Indices for Crop Health Monitoring

The calibrated UAV-acquired orthomosaics were used for calculating five VIs, many of which have been proposed as surrogates for canopy chlorophyll or nitrogen concentration estimation (Dunn *et al.*, 2017, Putra *et al.*, 2020, Walsh *et al.*, 2018). The VI index maps calculated and tested include:

- *Normalized Difference Vegetation Index – NDVI = (NIR − Red) / (NIR + Red)*
- *Leaf Chlorophyll Index – LCI = (NIR – Red-Edge) / (NIR + Red)*
- *Normalized Difference Red Edge – NDRE = (NIR – Red-Edge) / (NIR + Red-Edge)*
- *Excess Green Index – ExG = (2*Green – Red – Blue) / (2*Green + Red + Blue)*
- *Visible Atmospherically Resistant Index – VARI = (Green−Red) / (Green+Red−Blue)*

For each geo-tagged SPAD measured coffee tree, the coded tree crown was extracted from the GIS farm database and used to calculate mean value of each UAV-derived VI corresponding to that selected tree (with SPAD readings). In order to identify appropriate vegetation indices obtained from UAV images in estimating critical levels of chlorophyll or nitrogen concentration in Robusta and Arabica coffee plants, an empirical correlation analysis was conducted. Figure 5 shows significantly high correlation between SPAD readings and UAV-derived VIs indicating the significance of NDVI, LCI and NDRE as potential crop health indicators for coffee plant health/nutrient monitoring. Specifically:

- With 59 SPAD readings sampled for Robusta coffee trees in the Tan Chau-Di Linh area, the correlation between SPAD readings and NDVI, LCI or NDRE is significantly high (r = 0.703, r = 0.745 or r = 0.746 respectively with $p < 0.01$).
- With 39 SPAD readings sampled for Arabica coffee trees in the Da Nhim and Tram Hanh areas, the correlation between SPAD readings and NDVI, LCI or NDRE is significantly high (r = 0.672, r = 0.732 or r = 0.746 respectively with $p < 0.01$).

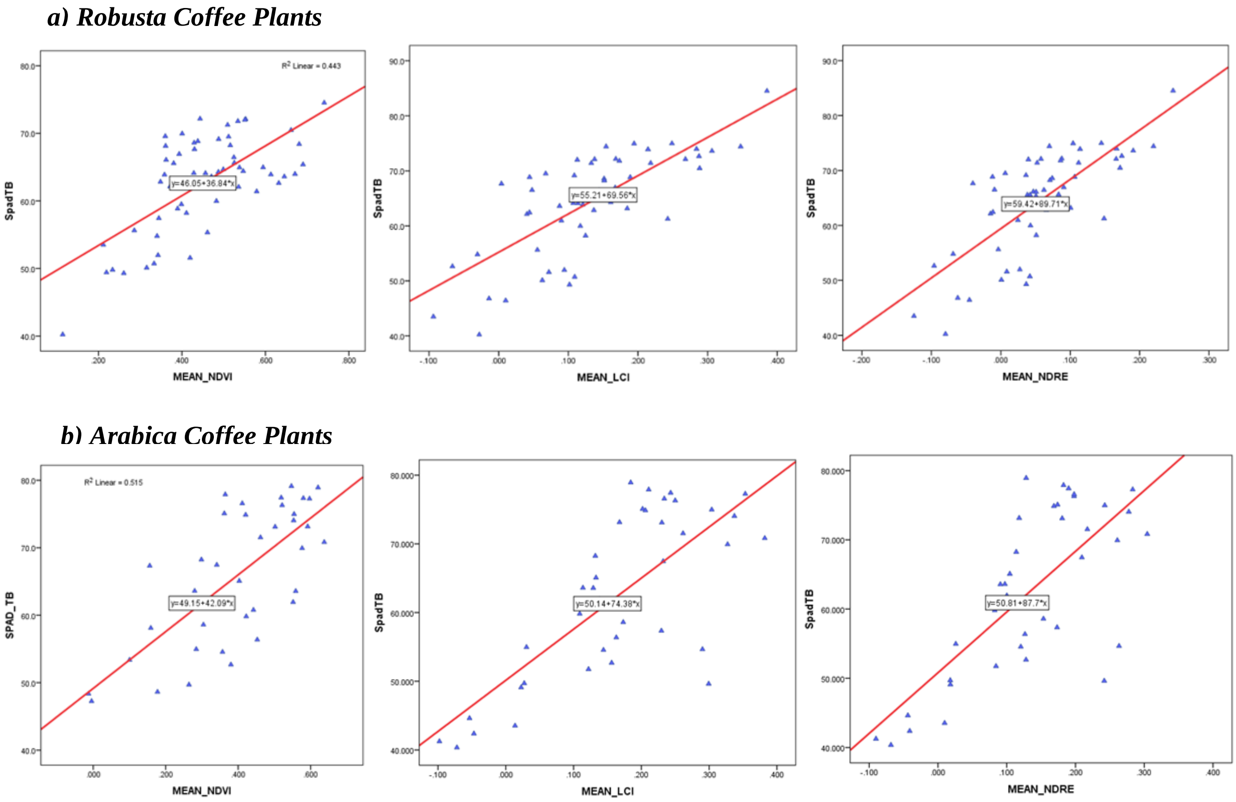


Figure 5. Scatterplots and Pearson correlation between SPAD readings and NDVI, NDRE and LCI

It worth noting that the sampled correlation between NDRE and LCI is almost perfect (r = 0.995, $p < 0.01$), meaning they provide almost identical information in terms of crop health and could be replaced by each other. The pixel-wise correlation between NDVI and NDRE was also found significantly high (r = 0.75-0.85, $p < 0.01$). However, NDVI is reportedly quickly saturating in dense vegetated areas such as production coffee farms and is less sensitive to small changes in canopy foliage content, gap fractions and senescence as compared to red-edge VIs (Putra *et al.*, 2020). Hence, NDRE was selected as the primary indicator for developing scoring parameters in this study for coffee farm health mapping and monitoring with NDVI as a supplementary indicator.

4. RESULTS AND DISCUSSIONS

4.1 Scoring Parameters for Coffee Farm Health Monitoring

In the context of scattered smallholder coffee farming, practical farm advice can be derived from farm-level analysis of UAV-captured information as farm owners usually apply farming efforts uniformly across their farm plots (e.g., blanket fertilizing, pesticide spraying) and efforts may vary from farmer-to-farmer. It is important to note that high resolution UAV mapping enables tree-level analysis focusing on specific coffee trees on respective farm plots supported by ground observations and measurements (such as SPAD readings). For this, the UAV pixel-level values (of respective VI index maps) within each tree crown (canopy) were used for parameterizing that coffee tree while for farm-level analysis, data aggregation from in-farm individual tree information for respective coffee farms can be used.

This approach reduced errors in coffee farm analysis by excluding pixel values (vegetation indices) of surrounding objects in the farm plot that were not coffee crops (e.g., shade trees, weeds or soil background).

Using the selected crop health indicator of NDRE, scoring parameters for coffee farm health mapping and monitoring were derived by geo-processing (e.g., overlay and statistical summation) of respected VIs - aggregating pixel values on extracted coffee tree crowns (Figure 4) and inside the respective coffee farm boundaries. As results, NDRE scoring parameters were calculated for all 558 delineated coffee farms in seven AOIs, including: (1) MEAN_NDRE - mean value of NDRE indicating averaged level of plant health/nutrient in a farm; and (2) STD_NDRE - standard deviation of NDRE indicating the level of uniformity (variation) of coffee plants (in terms of health/nutrient) across a farm. The statistics of NDRE scoring parameters by AOIs (acquired and computed) for all 4 UAV flight missions showed a general tendency of higher and relatively more uniform MEAN_NDRE (averaged leaf-nutrient levels) in Arabica coffee farms than in Robusta farms. Similarly, NDVI-based scoring parameters of MEAN_NDVI and STD_SDVI were calculated and used for complementary analysis and cross-inspection with NDRE-based coffee farm health mapping and monitoring. The time series of NDVI scoring parameters (Figure 6) confirmed the coffee phenological cycle of perennial crop plantations in the study area, where the MEAN_NDVI values for Robusta and Arabica coffee farms in all seven AOIs are consistently high (0.55 – 0.65) during the grain formulation and maturation stages (June-December period) with green leaves, but considerably decreased to 0.10 - 0.20 during the post-harvest and dormancy stages (December- March period) with clear senescence signs of yellowish leaves. Similar time pattern of relatively unchanged during July-December (threshold value of changing defined as ΔMEAN_NDRE = 0.02) and a sharp decrease in average NDRE scores during December-March (threshold value of changing defined as ΔMEAN_NDRE = -0.03÷-0.06) was only observed for Robusta coffee farms in AOIs V3.1 Tan Chau, Tan Thuong and AOI V3.2. The significant lower chlorophyll (nutrient) content in Robusta leaves in March can be explained by the fact that those Robusta farms were intentionally left dry without fertilizing (for bud formation before flowering) at that time and so, with dry soil moisture, nutrients (if any left from previous season) were difficult to transfer from soil up to branches and leaves. And for this reason, the NDRE score is a good indicator for water stress (which usually comes along with nutrient deficiencies). For rain-fed Arabica coffee farms in AOI V3.3, V3.4, V3.5, V3.6 and V3.7, variations in average NDRE scores were relatively small (threshold value of changing MEAN_NDRE for Arabica farms defined as ΔMEAN_NDRE = 0.025) over a one-year cycle and no significant decreases in NDRE were found during the December-March period.

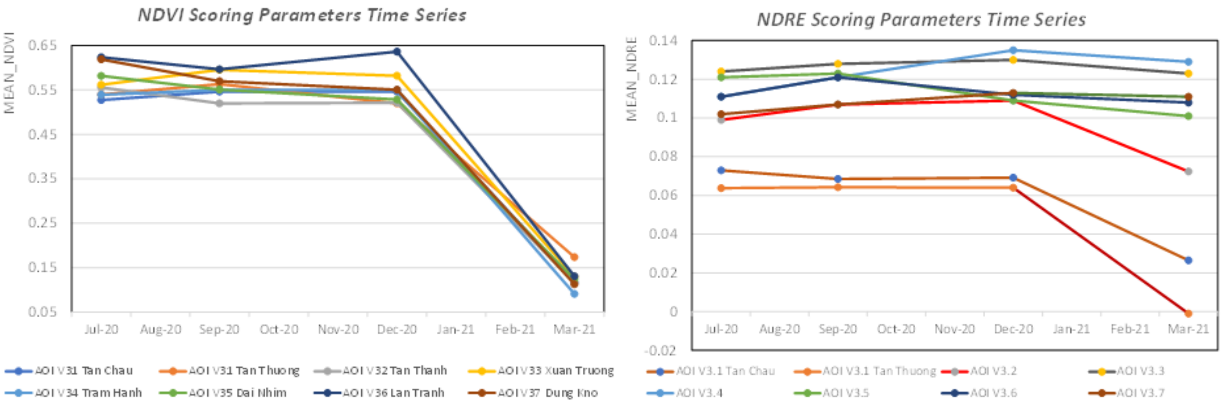


Figure 6. Time series of NDVI and NDRE (mean) scores for one-season cycle for coffee farms in seven AOIs

In terms of intra-plot variation of coffee farms in seven AOIs, the STD_NDRE scores can be used as an indicator to assess abnormal changes in coffee tree foliage varying within a coffee farm – uniformity levels of plant growth, which could be caused by potential pest and disease attacks (Katsuhama *et al.*, 2018, Kuckenberg *et al.*, 2009). Analyzing its value distribution with field inspections and SPAD readings, the STD_NDRE threshold value for disease-affected farms was defined around 0.07(±0.02). And these thresholds were used in combination with time series data to see if STD_NDRE increases or decreases over successive mapped data (from July to September 2020, or so) in order to confirm pest or disease incidences (progressing or healing). The threshold value in changing STD_NDRE score was defined as ΔSTD_NDRE around ±0.025.

4.2 Coffee Farm Ranking by Plant Health/Nutrition Conditions

Analyzing the value ranges and histograms of the computed NDRE scoring parameters and cross-reviewing with field inspections and measurements showed that geo-tagged good-nourished coffee trees with SPAD readings were observed with high MEAN_NDRE scores (0.25 – 0.35) while under-nourished trees (as indicated by yellowish leaves, or with visible nutrient deficiency symptoms) were observed with low MEAN_NDRE scores (-0.08÷-0.15) Considering the SPAD threshold readings on coffee plants with severe nutrient stress (as shown on scatterplots in Figure 5), the threshold values of MEAN_NDRE & STD_NDRE in July 2020 for coffee farm nutrient level ranking were defined for each of 7 AOIs (Robusta or Arabica farms) as shown in Table 2.

Table 2. Defined threshold values of MEAN_NDRE and STD_NDRE for ranking of coffee farms in terms of plant nutrient states in July 2020 in 7 AOIs (AOI V3.1 separated into Tan Chau & Tan Thuong sub-AOIs for its large area)

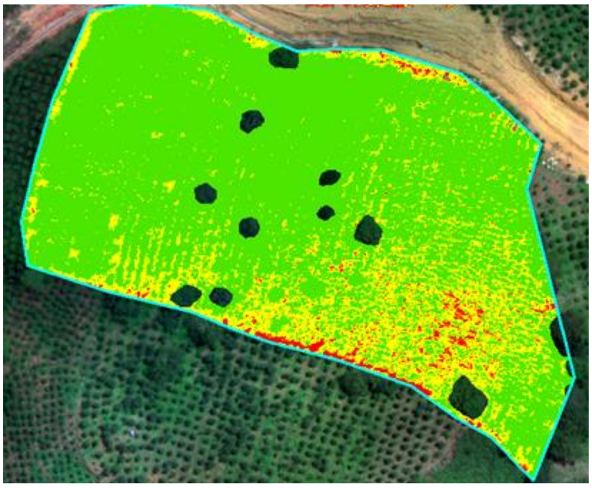
AOI (number of farms)	Low NDRE score (poor nutrition)		Medium NDRE score (average nutrition)		High NDRE score (good nutrition)	
	Mean	STD	Mean	STD	Mean	STD
AOI V3.1 Tan Chau (90)	< 0.03	Low: <0.056	0.03-0.08	Low: <0.06	> 0.08	Low: <0.085
		High: >=0.056		High: >=0.06		High: >=0.085
AOI V3.1 Tan Thuong (112)	< 0.04	Low: <0.06	0.04-0.011	Low: <0.075	> 0.11	Low: <0.085
		High: >=0.06		High: >=0.075		High: >=0.085
AOI V3.2 (45)	< 0.052	Low: <0.07	0.052-0.091	Low: <0.072	> 0.091	Low: <0.085
		High: >=0.07		High: >=0.072		High: >=0.085
AOI V3.3 (99)	< 0.05	Low: <0.07	0.05-0.15	Low: <0.08	> 0.15	Low: <0.08
		High: >=0.07		High: >=0.08		High: >=0.08
AOI V3.4 (43)	< 0.05	Low: <0.08	0.05-0.15	Low: <0.08	> 0.15	Low: <0.08
		High: >=0.08		High: >=0.08		High: >=0.08
AOI V3.5 (57)	< 0.047	Low: <0.075	0.047-0.15	Low: <0.08	> 0.15	Low: <0.08
		High: >=0.075		High: >=0.08		High: >=0.08
AOI V3.6 (35)	< 0.04	Low: <0.07	0.04-0.15	Low: <0.08	> 0.15	Low: <0.08
		High: >=0.07		High: >=0.08		High: >=0.08
AOI V3.7 (29)	< 0.03	Low: <0.08	0.03-0.09	Low: <0.067	> 0.09	Low: <0.08
		High: >=0.08		High: >=0.067		High: >=0.08

Combining the threshold values of MEAN_NDRE and STD_NDRE scoring parameters defined for July 2020, 558 coffee farms in 7 AOIs were classified (ranked) into six groups with different plant health / nutrition states, namely: (1) farms uniformly with good health/nutrition, (2) farms with good health/nutrition but highly varied, (3) farms relatively uniform with average health/nutrition, (4) farms with average health/nutrition and highly varied, (5) farms relatively uniform with poor health/nutrition, and (6) farms with poor health/nutrition and highly varied - with example farms shown in Figure 7. Ranked coffee farms in 7 AOIs were integrated into the GIS farm database as additional farm information for immediate farm advice as this classification helps indicate specific farm-level plant health/nutrition problems where possible causes of plant health stress may be highlighted. For example, farms with low and uniform NDRE score may be attributed to lack of fertilizing and/or aging plants while farms with highly-variable NDRE score may be caused by some disease or pest attacks. It is important to note that in addition to farm-level nutrient status, the NDRE scores provide pixel-based nutrient information of mapped coffee trees. For high variability coffee farms, the NDRE index maps can be masked by NDRE thresholds (e.g., 0.06(±0.02) for Robusta or 0.09(±0.02) for Arabica farms) in order map nutrient deficiencies in different parts of a farm for detailed farm advice.

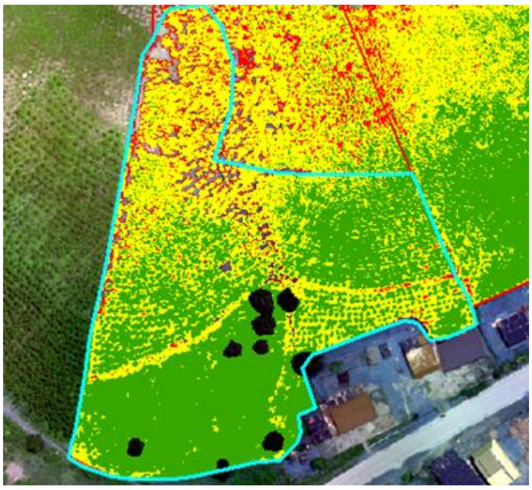
4.3 Coffee Farm Monitoring on Plant Health Stress

As coffee trees grow through its annual phenological cycle: supported by fertilizer/watering inputs and affected by certain external stressors, the farm-level plant health/nutrient status mapped in July 2020 was further monitored by MEAN_NDRE and STD_NDRE scoring parameters (acquired and similarly computed) for subsequent UAV mapped data. All 558 coffee farms in 7 AOIs were updated with ranked NDRE scores for September, December 2020 and March 2021 in the GIS farm database as farm monitoring information layer, based on which farm-level plant health/nutrition states with changes and possible plant health stress can be continuously detected. Similar to July 2020, threshold values for significant level of plant health/nutrient stress were defined for NDRE scoring parameters for 3 subsequent UAV mapping missions as shown in Table 3. Please note that the general trend of MEAN_NDRE shown in Figure 6 – mainly due to seasonal plant phenological changes - was taken into account in order to focus only on attributable plant health stress factors such as nutrient deficiencies, water stress and pest or disease incidences.

Group 1 - Farms uniformly with good health/ nutrition

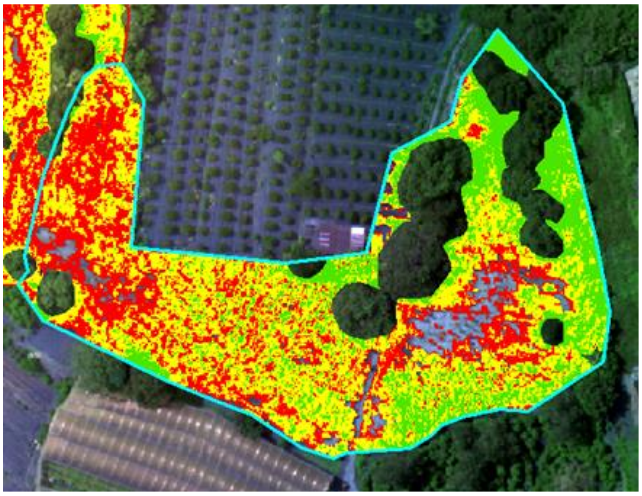


Group 2 - Farms with good health/nutrition but relatively varied

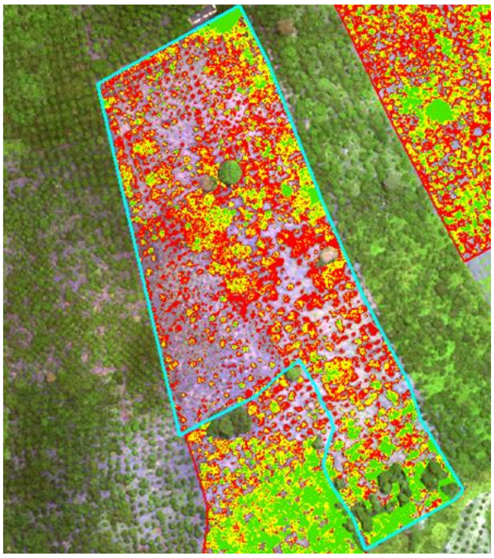


Group 3 - Farms relatively uniform with average health/nutrition

Group 4 - Farms with average health/nutrition and highly varied



Group 5 - Farms relatively uniform with poor health/nutrition



Group 6 - Farms with poor health/nutrition and highly varied

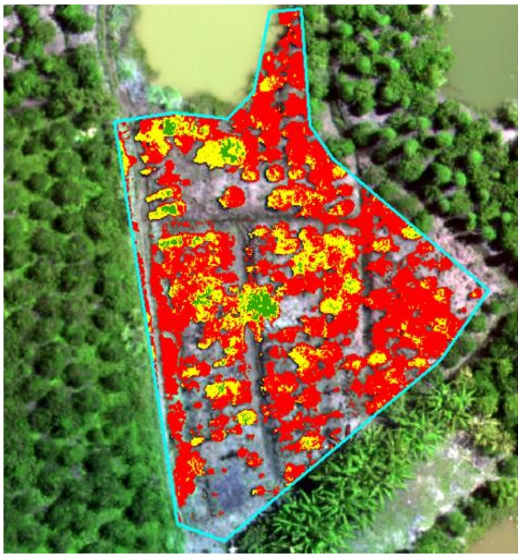


Figure 7. Coffee farms ranked by NDRE scores on plant' nutrient levels and intra-farm variations

Table 3. Threshold values of MEAN_NDRE and STD_NDRE scoring parameters for coffee farms in 7 AOIs with severe plant health/nutrient stress

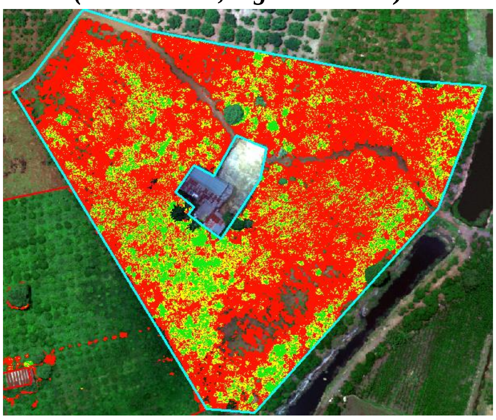
AOI (number of farms)	July 2020		September 2020		December 2020		March 2021	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
AOI V3.1 Tan Chau (90)	0.03	0.079	0.029	0.078	0.028	0.08	0.007	0.077
AOI V3.1 Tan Thuong (112)	0.041	0.081	0.039	0.087	0.038	0.11	0.001	0.082
AOI V3.2 (45)	0.052	0.082	0.067	0.0796	0.069	0.0826	0.034	0.0797
AOI V3.3 (99)	0.050	0.075	0.052	0.076	0.054	0.078	0.051	0.074
AOI V3.4 (43)	0.050	0.076	0.051	0.074	0.055	0.077	0.052	0.076
AOI V3.5 (57)	0.047	0.074	0.052	0.076	0.049	0.077	0.046	0.075
AOI V3.6 (35)	0.040	0.077	0.051	0.082	0.052	0.087	0.048	0.076
AOI V3.7 (29)	0.030	0.069	0.032	0.072	0.035	0.074	0.033	0.068

Using these threshold values, unhealthy and under-nourished farms (i.e., with low MEAN_NDRE below thresholds) and/or highly-varied farms (high STD_NDRE above thresholds) were identified and verified by field inspections as farms with severe plant health/nutrient stress. In order to detect potential signs of pests or diseases infection, intra-plot variations of NDRE scores in July 2020 were carefully examined in highly-varied sub-areas with low MEAN_NDRE highlighted and filtering out other plant-health factors, such as weeds infestations, varying slopes, etc. As results, 'indicative pest or disease signs' in 39 coffee farms were detected for subsequent field inspection and verification. Further analyzing STD_NDRE scores in September, December 2020 and March 2021 (using its threshold values for each of three stages in Table 3 and threshold value of changing ΔSTD_NDRE=$\pm$0.020) helped confirmation of infected farms and its progression or regression (healing) of disease infection. Figure 8 shows a Robusta coffee farm in AOI V3.2 - with severe nutrient deficiencies and heavily affected by Nematodes, whose infection was considerably progressed during the July 2020 – March 2021 period as evidenced by the UAV-derived NDRE scoring parameters and verified by field inspection/SPAD measurement (Figure 2).

NDRE score map in July 2020 (mean=0.049, high std=0.069)

NDRE score map in September 2020 (mean=0.051, high std=0.072)

NDRE score map in December 2020 (mean=0.058, high std=0.073)



NDRE score map in March 2021 (mean=0.026, high std=0.074)

Figure 8. Robusta coffee farm in AOI V3.2 with progressing heavy nematodes infection

5. CONCLUSIONS

To monitor plant health in smallholder coffee plantations, different VIs were computed using UAV images and compared with the coffee leaves' chlorophyll contents measured by the SPAD-502 Chlorophyll Meter during ground truthing during the 2020-2021 crop season. Based on the observed significantly high correlation with geo-tagged SPAD readings, NDRE and NDVI were selected as the most appropriate crop health indicator. This study focused on developing efficient NDRE and NDVI-based scoring parameters as means and standard deviations of 'within-coffee -canopy-only' pixel values, which allows for focused assessment of coffee plant health. Analyzing NDVI and NDRE scoring parameters in time series comparing with coffee seasonal phenological cycle in the study area confirmed NDVI as general plant health index (indicating bundled leaf greenness with clear senescence signs at the end of dry season) and NDRE as plant nutrient index (indicating soil quality and fertilizer input with water stress limiting nitrogen uptake at the end of dry season). Utilizing both MEAN_NDRE and STD_NDRE scores, 558 Robusta and Arabica coffee farms in seven study AOIs were ranked by its averaged plant/nutrient level together with intra-plot nutrient variability in July 2020, which was updated in September, December 2020 and March 2021. Considering SPAD threshold readings on coffee plants with severe nutrient stress, specific threshold values of MEAN_NDRE were defined to identify coffee farms with severe nutrient deficiencies, while threshold values of STD_NDRE helped to detect potential signs of pests or diseases infection in 39 coffee farms in the study area. The STD_NDRE scores in subsequent timelines (e.g., September, December 2020 and March 2021) were used to track, confirm of infected farms and/or identify its progression or regression (healing) of disease infection. In addition, all these generated scoring information were frequently updated and managed in the GIS farm database for integrating with reference data in further analysis for practical and timely farm advice.

The results presented in this paper show that UAV-based VIs, especially NDRE can be effectively used in continuing plant health/nutrient monitoring of smallholder coffee farms and early detection of water stress and pest or disease attacks. It is expected that our approach with some analytical streamlining in an integrated farm monitoring system can be successfully applied to other coffee plantation area.

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