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Improving nitrogen assessment with an RGB camera across uncertain natural light from above-canopy measurements

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Abstract

The farming activities in developing countries are mostly conducted in daytime with varying intensities of natural light throughout the day. Also, the shade trees can further increase the uncertainty of natural light exposure on plants. This research proposes an appropriate method to standardize index values obtained from an RGB digital camera for assessing biophysical properties, especially nitrogen content. Nutrient content in plants is an important factor that characterizes plant yields and health. Determining the status of plant nutrients often requires field observation. The conventional laboratory methods and remote sensing applications (i.e. satellite, airborne and spectrometer) are still expensive. Also, weather and field condition significantly affect the quality of measurement results. The use of consumer-grade digital cameras has been explored as an alternative low-cost tool for non-scientific end users; however, the use of a camera for above-canopy measurement is severely constrained by unfavorable weather condition coupled with limited time available for the measurement that depends on the intensity of incident light and the condition of plantation area. Furthermore, shade trees present in plantation areas reduce the quality of measurement results. By using this newly proposed method, measurement accuracy is improved and the potential use of Red, Green, and Blue (RGB) cameras during daytime is explored. Since many studies showed that the Hue index was a potential tool for estimating biological properties, this study used exposure value (EV) to adjust the digital number (DN) and Hue index to observe the potential of calibrated and standardized DN and Indices for estimating greenness of Robusta coffee plants.

Keywords Broadband greenness · Standardization · Above-canopy measurement · Chlorophyll · Nitrogen content · Coffee plant

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Introduction

Estimating biophysical properties like chlorophyll and nitrogen content of vegetation using digital cameras may produce different results, depending on the time of measurement. Even when measurements conducted on the same day, the value of indices may notably vary according to the time of the day, thus causing erroneous estimation of plant biophysical properties. Nitrogen (N) management is a key to increasing the sustainability (Masunga et al. 2016; Raun and Johnson 1999) of crop production. Both excessive and inadequate fertilization of N are common problems in Indonesian coffee production. Excessive N fertilization increases pollution and lowers economic return, as well as the quality and quantity of yields. Inadequate fertilization could make plants more vulnerable to pests and diseases, thereby reducing production quality and quantity.

Precision agriculture using aerial remote sensing (Aasen et al. 2015; Jia et al. 2004; McNeil et al. 2016; Toth and Jóźków 2015) improves crop productivity by supplying plant-specific inputs. However, Robusta coffee plantations are the exception for aerial remote sensing implementation, because they are situated in hilly areas, covered by shade trees, and contain plants of different growth stages within an area. The use of ground-based sensors is usually recommended to address these problems. The ground-based commercial nitrogen sensors such as CropSpec®, Green Seekers® and Crop Circle® are popularly used for cereal plants. These active nitrogen sensors are not affected by ambient light intensity and could be mounted on a tractor or a modified platform, provide information similar to sensors on aerial vehicles and satellites, and overcome some of the logistical limitations of remote sensing. However, these tools are still expensive for the farmers/smallholders in developing countries.

A potential method to overcome these limitations is using consumer-grade digital cameras. Recent studies have successfully assessed the biophysical properties of vegetation through the direct-leaf measurement using digital cameras (Rigon et al. 2016; Vesali et al. 2015, 2016; Widjaja Putra and Soni 2018). In these studies, the Hue index is shown to have offered better accuracy than other vegetation indices (VIs). However, compared with direct-leaf measurement, the above-canopy measurement is more efficient, but it practically lacks accuracy in fields having shade trees and under uncertain natural light. Without calibration and standardization of the digital number (DN) or VI for prevailing incident light intensity, it loses accuracy. A DN of a digital camera image is obtained by extracting the value of every pixel of each RGB band. Then, these two or three extracted DNs of each RGB band can be incorporated as indices. Unlike a spectrometer that can be standardized with the reflectance value through a white panel (spectralon), a digital camera needs to be calibrated and standardized in different ways. Few studies are reported on how to standardize the incoming light intensity towards the available VIs value obtained from digital cameras through above-canopy measurement. Long-term use of calibration and standardization models of digital cameras is difficult to achieve, in part because of frequent product upgradation by camera manufacturers. Several studies suggest ways to eliminate the effect of uncertain illumination using digital cameras. Bourgeon et al. (2016) offered a technique for radiometric calibration under natural illumination using a color-board checker. Sakamoto et al. (2010, 2012) showed the potential of calibrating the DN with relative light intensity (RLI) to eliminate the effect of uncertain illumination, like the gamma factor which has a non-linear relationship between DN and the intensity of incident light. Gamma is a non-linear operation used to shifting and scaling the luminance in image (Reinhard et al. 2001). Although these findings show the potential use of the consumer-grade camera for crop monitoring, detailed field assessment is required to evaluate such methods for plant monitoring from above-canopy measurement under uncertain natural light.

The main objectives of this study were to evaluate the use of a consumer-grade camera for estimating biophysical properties such as chlorophyll and N contents of Robusta coffee plants under varying natural light conditions. The use of VI by incorporating multiband is still considered not optimal in estimating biophysical properties such as chlorophyll and N content, under uncertain natural light conditions. Hence, exploring the VIs that can be implemented in various measurement methods, both direct-leaves and above canopy measurements is considered worthy. Further, influence of using different DNs such as calibrated and standardized, is compared. Considering the importance of calibrated and standardized DNs obtained from digital camera applications, this study aimed at the following specific objectives. First, it evaluated the proposed methods that incorporate the EV to standardize the available VIs for the different natural light condition without any additional sensors. Second, it examined the DNs (both calibrated and non-calibrated) used in the Hue index for estimating leaf greenness of Robusta coffee for estimating plant N content across different natural light conditions. Lastly, it evaluated the VIs obtained from a commercial-grade camera at different measurement levels (direct-leaf and above-canopy measurements).

Materials and methods

This study comprised of two sets of experiments. The first experiment evaluated the VI of colors panel under different natural light, which aimed to determine relationships between EV and VI of a consumer-grade camera. The second experiment assessed the chlorophyll and N level of Robusta coffee plants by identifying the greenness level from the above-canopy measurement.

Panels measurement

To test the sensitivity of VI across different illumination levels, a set of RGB cameras (Canon IXUS 160) were installed on a platform aboveground (Fig. 1) and placed in an open field. Cameras were aimed at the nadir position towards the object at various distances ranging from 0.5 to 1.5 m. This study focused on both green and yellow colors (Seculine ProDisk II with white balance filter). The camera configuration with auto-white balance, auto-focus, and auto-exposure time was used in both panel and field measurements. A total of 120 images were saved with 20 megapixels resolution, in JPEG (3864 × 5152 pixels) format.

In this experiment, the two panels represented the greenness of leaves, where the greenness could be an indicator for estimating the chlorophyll and nitrogen content of the vegetation (corresponding to Fig. 3). These panels were used as references for further in situ measurement of plant leaf greenness and to standardize the VI.

In-situ measurement

This set of experiments builds on the study of Widjaja Putra and Soni (2017) which enhanced potential use of cameras from direct-leaf to above-canopy measurement. For this purpose, a custom platform for attaching the camera was developed (Fig. 1). Direct-leaf measurement was conducted on the same plant within the same day for comparing

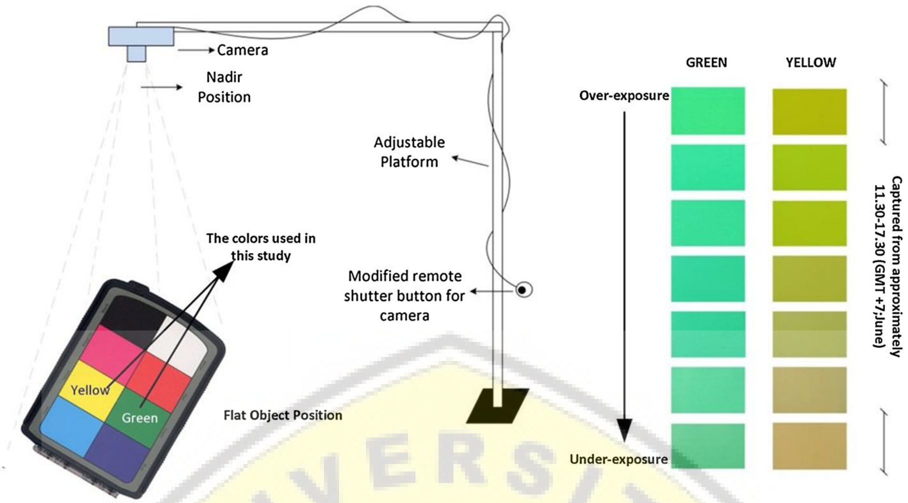

Fig. 1 Image capturing using digital camera with a platform (left). Green and yellow colors across different illumination from over-exposure to under-exposure (right) (Color figure online)

above-canopy and direct-leaves measurements, while the destructive analysis of N was done in the laboratory. The destructive analysis examined leaf tissues of each plant that underwent the previous set of all non-destructive measurements. To minimize error in identifying plant properties, only plants and leaves that were free from pests and diseases were chosen.

Experiments were conducted at the Indonesia Coffee and Cocoa Research Institute (ICCRI), Jember, Indonesia (8°15′24.6″S 113°36′45.1″E) located in East Java, Indonesia. Robusta coffee plants were chosen randomly from different growth stages, ranging from 2 to 10 years across different field shading conditions.

Leaves greenness through canopy measurement

A total of 320 images were collected from 40 plants using a digital camera. Average values from four repeating measurements were used to compute the VIs to represent each plant's chlorophyll and N concentrations. Images were captured during 08.00 to 16.00 h. The digital number (DN) of infrared, background exposure and exposure-value (EV) tends to increase as the distance between the camera and object increases (Sakamoto et al. 2011b). In these experiments, the distance between camera and plant was determined based on the camera's ability to adequately capture canopy cover or leaf area of the plant. Wilted leaves can make the canopy cover smaller and increase the soil or background visibility. The targeted object area or region of interest (ROI) was targeted within the camera frame. In this in situ measurement, the camera configuration involved auto white balance, auto-focus, and automatic exposure time. Black cloth was used as background to avoid error in extracting the image value due to foliage plant and weeds. For the analysis, the canopy above the cloth background or plant leaves area was selected as the ROI (Fig. 2).

Fig. 2 **a** Above-canopy measurement images of Robusta coffee plants with different soil background. **b** Manual selection of ROI of the canopy/leaves area

Direct-leaf measurement and N laboratory analysis

For this measurement, leaf number-2 (in drought/rain-fed areas) and leaf number-3 (in irrigated areas) were chosen from selected plagiotropic branches counting from the apex, a total of 15 leaves were subsequently collected and labeled for further destructive examination (Widjaja Putra and Soni 2018). According to ICCRI (1999), 15 leaves should be taken from each Robusta coffee plant for laboratory measurement purposes. Thus, these leaves were measured using direct-leaf measurement before the N laboratory analysis. A SPAD-502 m was used in assessing Chlorophyll content through direct-leaf measurement. Direct leaf measurement and laboratory test were subsequently used for data validation.

The N value was determined by destructive measurement following the Kjeldahl procedure (Muñoz-Huerta et al. 2013). For sampling, 15 labeled leaves per plant were chosen from previous experiments to generalize the N content in plants. The collected leaves from each plant were stored using paper bags and brought to ICCRI laboratory for chemical analysis. The percentage nitrogen content in the leaves was estimated. Taken from 40 plants, a total of 600 leaves were measured in this experiment. Willson. (1985) categorized the N content of Robusta coffee plants into four different critical levels, namely deficient, subnormal, normal, and high with the percentage N contents (weight/weight) of: < 1.8%, 1.80–2.70%, 2.71–3.30%, and > 3.30% respectively.

Vegetation indices

Data collected from the field experiment using non-destructive measurement were mainly tested using exposure-value referenced vegetation indices for estimating chlorophyll and N concentrations. Previous studies (Rigon et al. 2016; Vesali et al. 2015) demonstrate that the Hue index provides better results than other vegetation indices in estimating plant greenness levels. In this study, Hue was examined using DN, calibrated DN (cDN), exposure value-adjusted cDN (ev-cDN), exposure-value referenced DN (evDN), exposure-value referenced cDN (evcDN), and exposure-value referenced DN-adjusted (evDN).

Procedure suggested by Sakamoto et al. (2010, 2012) are used in calibrating the DN of JPEG images against relative light intensity (RLI) for plant monitoring. Thus, by using this method, gamma characteristics of captured images can be corrected using a six-degree polynomial equation (Eq. 1) and the need for a calibration panel and an additional sun irradiance sensor to obtain radiometric calibration can be eliminated, like that available in Micasense RedEdge® camera. The two equations (Sakamoto et al. 2011a, b) to obtain cDN are expressed as following (Eqs. 1 and 2)

$$\mathrm{RLI} = ax^6 + bx^5 + cx^4 + dx^3 + ex^2 + fx \tag{1}$$

$$\mathrm{cDN} = \alpha \mathrm{RLI} + \beta \tag{2}$$

where x is the DN, $a = 2.540 \times 10^{-15}$, $b = -1.325 \times 10^{-12}$, $c = 2.383 \times 10^{-10}$, $d = -1.374 \times 10^{-8}$, $e = 1.372 \times 10^{-7}$, $f = 6.217 \times 10^{-5}$, $\alpha = 3658$, $\beta = 0.1045$, and cDN is the daily median value for daytime. The additional information for recognizing light intensity of captured images are obtained from EV, as EV can be used for adjusting the cDN (Nguy-Robertson et al. 2016) (Eqs. 3 and 4).

$$\mathrm{EV} = 2 \cdot \log_2(\mathrm{F}) - \log_2(\mathrm{T}) - \log_2\left[{}^{\mathrm{ISO}}/_{min\mathrm{ISO}}\right] \tag{3}$$

$$\text{ev-cDN} = \mathrm{cDN} \times 2^{\mathrm{EV}} \tag{4}$$

EV, F, T, ISO, and *min*ISO correspond to the exposure value of each camera, relative aperture, exposure time (f-stop), ISO sensitivity of the captured image, and minimum ISO of the camera, respectively. These values are recorded in the JPEG format header of each image. This camera has minimum daytime ISO values of 100.

Unlike some previous studies (Sakamoto et al. 2011a, b, 2012) which applied EV for DN adjustment, this study proposed three methods for adjusting the Hue index, namely exposure value − DN (evDN), exposure value − cDN (evcDN) ratios (Eqs. 5 and 6) and standardization of EV/VI against EV reference (Fig. 3). For the third method, the concept is expressed in the flowchart (Fig. 3b). Overall, Hue index was examined using these proposed methods. The VIs used in this study are listed in Table 1.

$$\mathrm{evDN} = \mathrm{EV}/\mathrm{DN} \tag{5}$$

$$\mathrm{evcDN} = \mathrm{EV}/\mathrm{cDN} \tag{6}$$

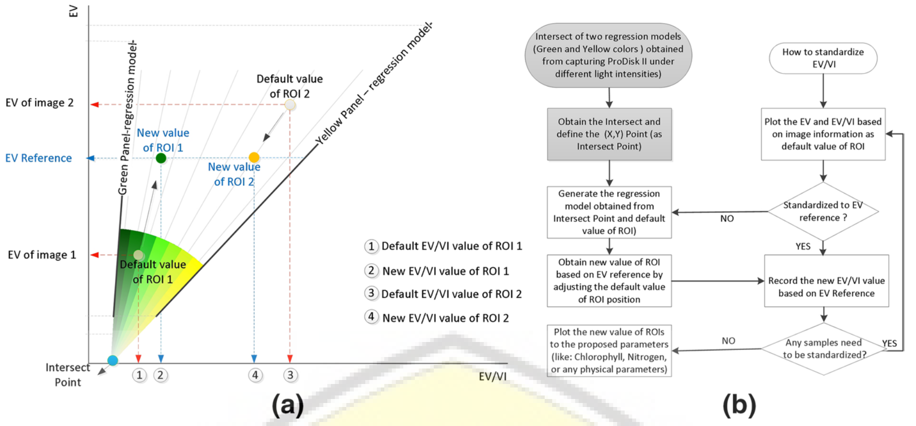

Fig. 3 The procedure in standardizing EV/VI against EV reference; proposed concept (**a**). Flowchart of standardizing the EV/VI (**b**)

Table 1 RGB camera-derived vegetation indices

Vegetation index	Formula	Reference
Hue	If $\max(R,G,B)=R$, $\frac{60(G-B)}{[\max(R,G,B)-\min(R,G,B)]}$ If $\max(R,G,B)=G$, $120+\frac{60(B-R)}{[\max(R,G,B)-\min(R,G,B)]}$ If $\max(R,G,B)=B$, $240+\frac{60(R-G)}{[\max(R,G,B)-\min(R,G,B)]}$	Rigon et al. (2016), Vesali et al. (2015)
cHue or ev-cHue	R,G,B altered to cDN_R, cDN_G, cDN_B or R,G,B altered to $cDN_R \times 2^{EV}$, $cDN_G \times 2^{EV}$, $cDN_B \times 2^{EV}$	(This study); modified from Sakamoto et al. (2011b, 2012)
evHue	R,G,B altered to EV/DN_R, EV/DN_G, EV/DN_B	(This study)
evcHue	R,G,B altered to EV/cDN_R, EV/cDN_G, EV/cDN_B	(This study)
ev/Hue	EV/Hue	(This study)
ev/Hue-adjusted	EV/Hue adjusted	(This study)
ev/cHue-adjusted	EV/cHue adjusted	(This study)

Results and discussion

Performance of indices with colored panels

In total, 120 images were collected from both green and yellow colors and subsequently analyzed. Calibrated and non-calibrated DNs of each color were used to estimate the Hue index and EV/Hue ratios. Figure 4a shows the strong relationship between EV against EV/cHue, and EV against EV/Hue of both green and yellow colors. However, the cHue index varies in a narrower range than Hue. Several observations are noted from the results (corresponding to Fig. 3). First, the minimum EV of the camera for capturing the objects using natural light can be identified, which is the intersection point between EV/Hue_{GREEN} and EV/Hue_{YELLOW} or using calibrated-Hue ($EV/cHue_{GREEN}$ and $EV/cHue_{YELLOW}$). Second, the capabilities of calibrated and non-calibrated Hues to identify different intersect points,

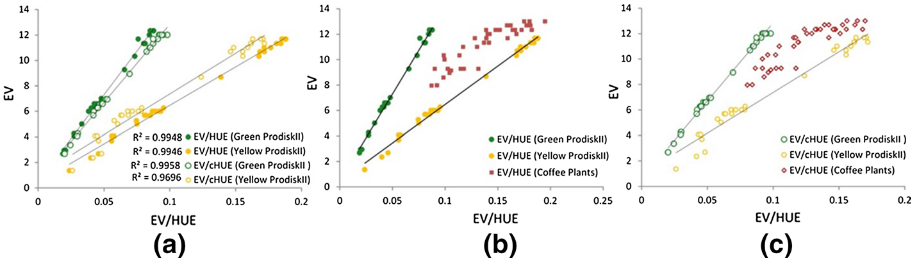

Fig. 4 Relationships between EV and EV/Hue using colored panel and field measurements; Comparison between Calibrated Hue and uncalibrated Hue using colored panel (**a**). The uncalibrated Hue (**b**) spread wider than the calibrated Hue (**c**) (Color figure online)

which means that the minimum EV (obtained through the intersection point) of calibrated Hue and non-calibrated Hue is different. Third, by plotting any samples obtained from field measurement, the level of exposure condition and plants' foliage color distribution can be identified. For example, Fig. 4b, c show calibrated and non-calibrated samples obtained from above canopy measurements. The samples which are close to the regression line of green panel indicate more greenness than those that are close to the regression line of yellow panel.

Application in a coffee plantation

Effect of light incident at camera

EV is affected mainly by F, T and ISO. During the day, the F and ISO values tend to be static (Sakamoto et al. 2011a, b). The influence of incoming light intensity at the time of above-canopy measurement is compared using DNs and calibrated DNs to show the distribution of coffee plants in the plantation (Fig. 4b, c). In this study, the shade trees were located in the managed/irrigated areas. Shade trees reduced the amount of incoming light intensity in the field, indicated by low value of EV. However, yellow or yellowish plant leaves are found in drought/rain-fed plantations with fewer or no shade, indicated by the higher value of EV. Thus, plantation areas with insufficient shade trees increased light intensity. Viewed from an agronomic perspective, evapotranspiration increases due to the lack of shade trees, which is indicated by wilted plant leaves resulting from the lack of water (Campanha et al. 2004). Water is needed to assist the absorption of nutrients by the roots. Limited availability of water in the soil limits the absorption of nutrients, causing nutritional deficiencies including N.

Performance of digital cameras with SPAD and N laboratory

The proposed method incorporating a consumer-grade camera as low-cost device for predicting chlorophyll and N content is optimized to represent greenness level of plant leaves. The relationships between 40 Robusta coffee plants (Plant leaf analysis using Kjeldahl and SPAD meter values) and proposed indices obtained from the camera were calculated and compared. The indices comprising of calibrated DN and un-calibrated DN are shown in Fig. 5. Hue and cHue values respectively showed substantial correlation with SPAD values and N concentrations. Among calibrated and non-calibrated indices, the same patterns of

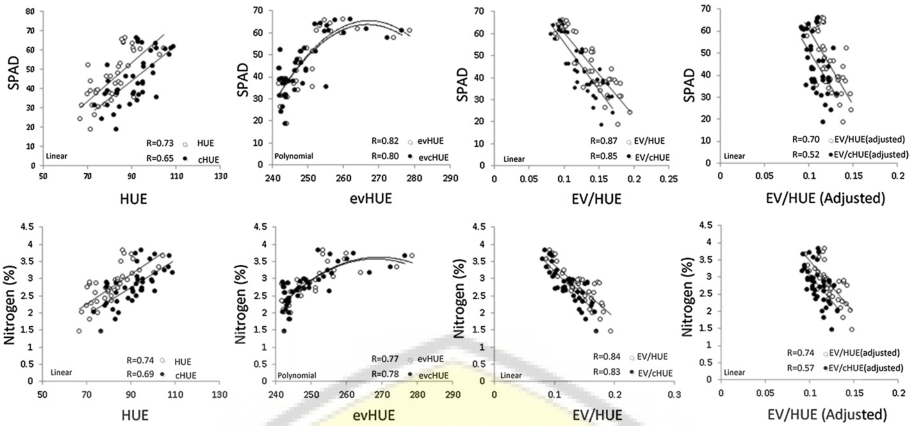

Fig. 5 Relationships between SPAD and VIs (above), and relationships between N laboratory and VIs (below)

regression, be it linear or polynomial, are likely to occur. In some indices like evHue and EV/Hue, EV improved the correlation. Nevertheless, EV/Hue$_{\text{Adjusted}}$, which adjusts the Hue index to same EV for each image (corresponding to Fig. 3), decreased the correlation. Relevant information in the form of JPEG images needed in this study (EV/cHue$_{\text{Adjusted}}$), like DN information of particular ROI in different exposure. This is because JPEG images are already refined than unprocessed format (RAW) (Lebourgeois et al. 2008).

The correlation results indicate that the regression models identify differences between calibrated and non-calibrated indices. To ensure which model can be implemented for a commercial-grade cameras in different measurement circumstances, like direct-leaf and above-canopy measurements, the relationships between above-canopy and direct-leaf as found in previous works (Widjaja Putra and Soni 2017, 2018) should be probed further.

Relationships between above canopy and direct-leaf measurements using camera

In this step, Hue and cHue indices obtained from above-canopy measurement were evaluated against Hue index obtained from the direct-leaf level. These results showed that the use of Hues (above-canopy level) were not standardized, compared with SPAD and N contents. These regression lines of cHue of above canopy measurement offer better applicability with Hues of direct-leaf levels, which are identified using homogenous artificial lights and custom chamber. Although these Hues provide higher correlation coefficients (Fig. 5), it does not mean that these regressions can be used directly. Another measurement model at the direct-leaf level should be considered. The use of cHue obtained from above-canopy measurement showed better correlation in estimating chlorophyll and N contents than Hue. The estimation of chlorophyll and N using corresponding values of above-canopy cHue and direct-leaf Hue were consistent, although above-canopy Hue provides better correlation with this parameter. By using cHue, the gap of the regression line between above-canopy and direct-leaf measurements was minimized.

Therefore, standardization of index values needs to be considered for use at any measurement level. Thus, uniformity of values can be obtained (Fig. 6). In the same vein,

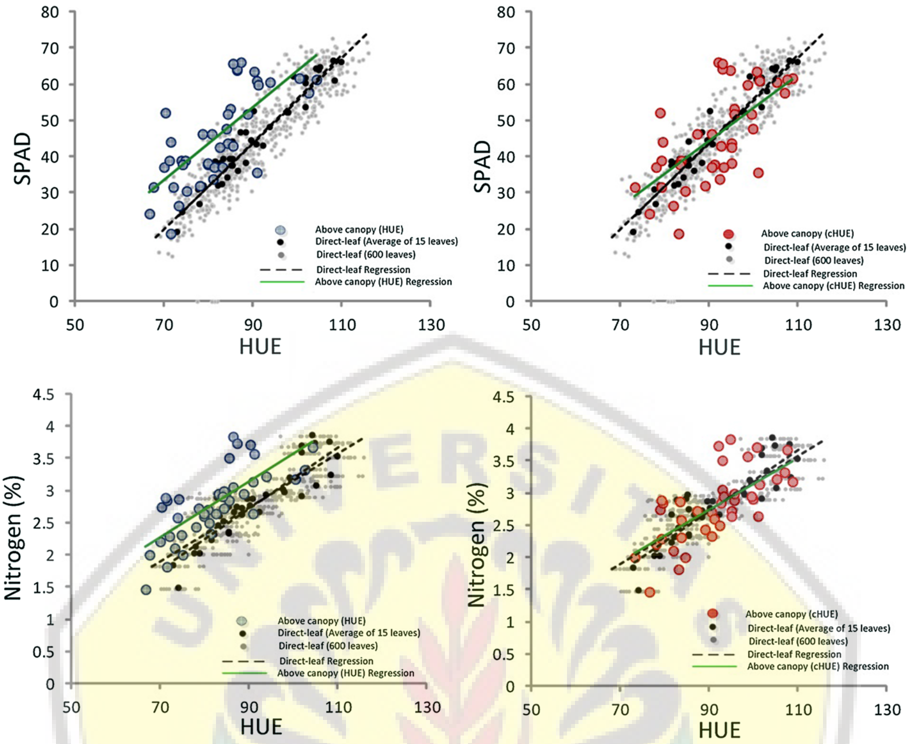

Fig. 6 Comparison between above-canopy and direct-leaf measurements using camera

Sakamoto et al. (2011a, b, 2012) suggested that indices using calibrated DNs result in stronger relationships with other sensors in obtaining biophysical parameters.

ROC analysis for evaluating the accuracy of N fertilization

In practice, coffee farmers in several countries resort to two sources of recommendations when applying fertilizer, which includes using general recommendations and relying on the analysis of leaf tissue (ICCRI 1999; Winston et al. 2005). However, the laboratory analysis generates the most appropriate recommendation. In this research, direct-leaf measurement provided a stronger correlation than above-canopy measurement in assessing N content.

To investigate the performance of suggested methods in estimating N content from above-canopy measurement, a receiver operating characteristic (ROC) analysis was conducted. In this analysis, the data were split into two event categories based on N laboratory tests. The first category was applying the fertilizer when the amount of nitrogen was low and deficient; and the second category was discontinuing the application of fertilizer when the amount of nitrogen was normal and abundant. Since the use of calibrated DN in Hue generated standardized results, the indices of cHue, evcHue, and EV/cHue were analyzed using ROC. The area under the ROC curve (AUC) was used to assess the predictive performance of proposed models for evaluation (Coudun et al. 2006). The results of ROC analysis are shown in Fig. 7.

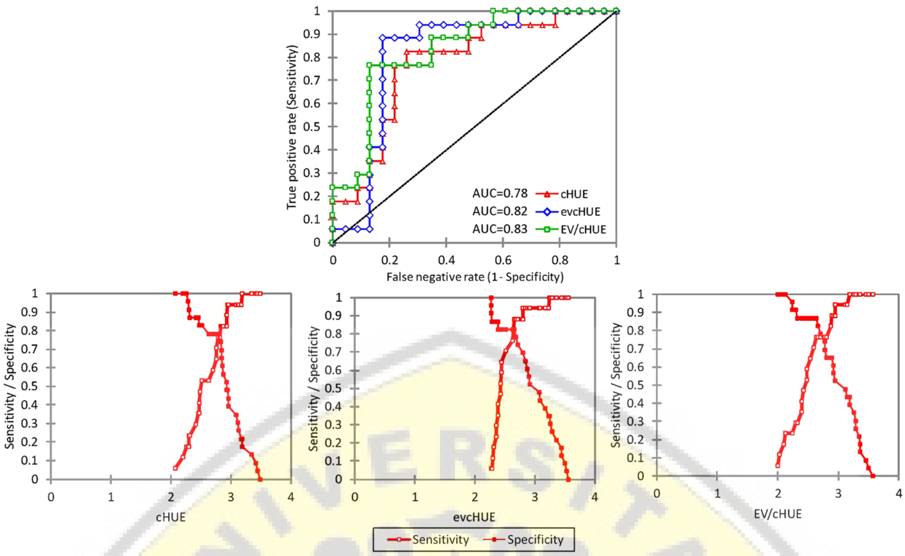

Fig. 7 ROC curves and area under curve (AUC) values of indices (above) and sensitivity and specificity of indices (below)

Figure 7 presents the accuracy of prediction models which are indicated by AUC values. This information shows that the proposed indices denote reliable basis for deciding as to how much N Fertilizer should be used for Robusta coffee plant.

Conclusion

Consumer grade digital cameras are an alternative tool for rapid monitoring of biophysical properties of the plant but their application is severely constrained under varying natural light condition and different measurement methods. This study has improved the potential of using consumer-grade digital cameras for measuring chlorophyll and nitrogen contents of broadleaf tropical Robusta coffee plants under uncertain natural light condition. The DNs were calibrated using RLI and/or EV to improve the relationship with chlorophyll and N, under uncertain natural light. It is confirmed that the use of cHue (comprising cDNs) for above-canopy measurement under uncertain natural lights showed comparable results with direct-leaf measurement using homogenous artificial light in assessing chlorophyll and nitrogen contents than Hue using DNs. It is also shown that the minimum threshold of EV camera can be determined by identifying intersect point of green and yellow indices of a color panel; which is useful to determine the capability of the camera for use in a particular range of exposure value under natural lights especially for agro-forestry measurement like in coffee plantation with very dense shade trees. Thus, EV should be considered as indicator of capturing the plant from above-canopy than timing of measurement alone.

The key conclusions of this study are listed as below.

1. Minimum threshold of EV camera can be determined by identifying the intersect point of green and yellow indices of the color panel. EV should also be recorded along with timing of measurement when capturing plants from above-canopy position.
2. Incorporating EV referenced DNs (i.e. EV/Hue, evHue, and evcHue) can improve the correlation. However, EV standardization should be considered. Incorporating EV referenced DNs can improve the correlation.
3. The use of calibrated indices acquired using a consumer-grade camera from above-canopy measurement under uncertain natural lights provides acceptable estimates of Chlorophyll and Nitrogen contents.

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