DETECTING THE IMPACT OF HAIL DAMAGE ON MAIZE CROPS IN SMALLHOLDER FARMS USING UNMANNED AERIAL VEHICLES DERIVED MULTISPECTRAL DATA

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ABSTRACT

Natural disasters such as hailstorms are now frequent and negatively impact smallholder farmers' livelihoods. In these events, there is a need for robust and innovative techniques for monitoring the extent of their damage in smallholder croplands to optimise production. In this regard, this study sought to evaluate the utility of drone-derived multispectral data in estimating crop health elements (i.e., equivalent water thickness (EWT), chlorophyll content, and leaf area index (LAI) of maize crops in smallholder croplands using the random forest regression algorithm. A hailstorm occurred in the study area during the reproductive stage 2 -3 and 3 to 4. EWT, Chlorophyll content and LAI were measured before and after the storm. Results of this study showed that there could be optimally estimated Equivalent water thickness, Chlorophyll content, and leaf area index based on the red edge and its spectral derivatives. Specifically, EWT was estimated to a RMSEs of 5.31gm^{-2} and 27.35 gm^{-2}, R^2 of 0.88 and 0.77, while Chlorophyll exhibited RMSEs of 87.4 and 76.2, and R2 of 0.89 and 0.80 and LAI yielded a RMSEs of 0.6 m^2 m^{-2} and 0.19 m^2 m^{-2}, before and after the hail damage, respectively. The findings of this study illustrate the prospects of utilizing UAVs in proximal sensing of crop productivity.

INTRODUCTION

The frequency of destructive weather events associated with climate change, such as thunderstorms, lightning and hailstorms, has increased, and with it, negative impacts of various magnitudes which are detrimental to the survival of humans (Raihan, Onitsuka et al. 2020). Developing countries, particularly the poor and marginalized rural communities, are the most susceptible to these events because they lack the resources and knowledge to implement robust adaptation and mitigation strategies. In sub-Saharan Africa, smallholder croplands dominate the agricultural sector, and these contributes to addressing hunger, malnutrition, and poverty and fostering food and nutrition security (Blair, Shackleton et al. 2018). Maize is one of the major crops grown in smallholder farms and contributes towards GDP, food, and nutrition security (Mashaba-Munghemezulu, Chirima et al. 2021), yet it is often exposed to natural disasters such as hailstorms storms. Early assessment of the impacts of hail on maize production could help determine the adaption strategy to minimize the risk associated with crop failure.

In smallholder systems, there are limited accurate and objective approaches that can be used to assess the spatial extent and magnitude of hail damage on crops. The approaches currently utilised in assessing the extent and magnitude of hail damage are limited to point-based laborious and time-consuming field surveys, that are lacking spatial representativeness (Singh, Saxena et al. 2017). Hence there is a need for objective approaches that can estimate the spatial extent and magnitude of damage to assist in the on-farm decision-making processes (Singh, Saxena et al. 2017). Remote sensing has emerged as the most robust, accurate and spatially explicit technique for assessing hail damage on the crop (Singh, Saxena et al. 2017).

Previous remote sensing-based research efforts were generally conducted in developed countries in commercial croplands based on sensors such as Landsat and Moderate-resolution imaging spectroradiometer (MODIS) and Sentinel 2 MSI data, amongst others (Prabhakar, Gopinath et al. 2019). Despite considerable successes associated with these studies, the generated conclusions and models were more applicable to commercial farms covering large areas, not smallholder croplands in developing countries which fragmented and are >2 ha. Meanwhile, crop attributes such as leaf equivalent water thickness (EWT), chlorophyll, and leaf Area Index (LAI) are related to the health and productivity of crops and have been successfully characterized using remotely sensed data in smallholder croplands. In this regard, EWT, chlorophyll content and LAI can be used as proxies for understanding the impact of hail damage on maize crops in smallholder croplands.

Unmanned aerial vehicles (UAVs) have presented better prospects of characterizing the spatial crop attributes in smallholder croplands than satellite-borne data. In this regard, UAVs offer ultra-high spatial resolution near real-time data on crop health and product attributes. To the best of our knowledge, very limited studies have been conducted based on UVA remotely sensed data in mapping the effect of hail damage in smallholder crops such as maize. This study sought to evaluate the utility of drone-derived multispectral data in detecting the changes in crop health and productivity elements (Equivalent water thickness (EWT), Chlorophyll content, and leaf area index (LAI)) of maize in smallholder croplands before and after a hailstorm based on the random forest regression ensemble.

MATERIALS AND METHODS

This study was conducted in Swayimane, a communal rural area within the uMshwathi local municipality in the KwaZulu Natal, South Africa (29°31'24' 'S; 30°41'37" E). Swayimani receives a mean annual rainfall between 600 mm and 1200 mm as well as an average annual temperature of 24 ºC. Most of the precipitation in Swayimane occurs in summer, and of late, there has been an increase in thunderstorms and hail events. Maize was planted in 3 plots measuring approximately 15m x 50m on the 8th of February 2021 and harvested on the 26th of May 2021 across a growth cycle of 108 days (Brewer, Clulow et al. 2022). The phenological growth stage of maize crops considered in the study was between the day of the year 41 to DOY 147. In this regard, a hail storm occurred on DOY 144 between the early (DOY 102) and mid-reproductive stages (118) of maize (Ndlovu, Sibanda et al. 2022).

Field sampling: A polygon was digitized around the experimental plot and saved as a keyhole markup language file (*.kml*). The *.kml* file was then used in ArcMap 10.5 to generate random sampling points where crop data was to be measured. It was also used to generate the flight plan to acquire the images. A total of 63 sampling locations were generated in a GIS.

These points were then imported into a hand-held Trimble Global Positioning System (GPS) with sub-meter accuracy for locating them. The maize plants that coincided with the location of the sampling point were marked and considered in this experiment. Then leaf area index, chlorophyll content and equivalent water thickness were measured before and after the hail storm (Ndlovu, Odindi et al. 2021, Brewer, Clulow et al. 2022). A Konica Minolta soil plant analysis development (SPAD) 502 chlorophyll meter (Minolta corporation, Ltd., Osaka, Japan) was employed to measure chlorophyll content on the adaxial maize leaf surface. The SPAD unitless values were converted to chlorophyll content in micromoles per square meter (μmol m-2) following the universal model derived by Markwell, Osterman et al. (1995) 's with R2 = 0.94 detailed below:

$$Chl\ (\mu mol\ m^{-2}) = 10^{s0.0265}$$

The SPAD meter readings were conducted on one leaf per plant. Specifically, the newest fully expanded leaf with an exposed collar and a minimum width of > 7 cm was considered to measure chlorophyll. A hand-held Li-Cor LAI 2200 plant canopy analyzer measured leaf area index estimates. In measuring each LAI estimate, five readings were conducted above and below the canopy of the maize plants. Initially, a reading was conducted above the canopy, and then four other readings were conducted below the canopy. The first fully developed leaf (first leaf below whorl) was acquired from the plants at each sampling point to measure the canopy equivalent water thickness of maize crops. Then a portable LI-3000C area meter in conjunction with the LI-3050C (Li-Cor, USA) transparent belt Conveyer with a millimetre resolution were used to measure the leaf area (A). The leaf's fresh weight (FW) was then measured using a calibrated digital scale with a 0.5g measurement error. The samples were then stored in brown paper bags, labelled accordingly, and taken to the laboratory, where they were oven dried at 70ºC until a constant dry weight (DW) was attained. Subsequently, the FW and DW were then utilized to derive EWT using the following formula:

$$\mathrm{EWT}_{\mathrm{leaf}}\ (\mathrm{gm}^{-2}) = (FW - DW) / A.$$

All field measurements were conducted between 1200 and 1400 Hrs to coincide with the image acquisition time. All data we combined in an excel spreadsheet and converted into a point map in ArcGIS.

Remotely sensed data

In this study, a MicaSense Altum multispectral sensor mounted on a DJI Matrice 300 remotely sensed maize crops. The Altum multispectral sensor acquires remotely sensed data in the blue (475 nm), green (560 nm), red (668 nm), red-edge (717 nm), NIR (840 nm) and thermal (8000-14000 nm). To acquire the image, the generated *.kml* file of the field boundary was imported into the drone controller and used to generate an automated flight path. The acquired images had a resolution of 2064 × 1544 at 120 m (3.2 megapixels per multispectral band) and a ground sample distance (GSD) of 5.2 cm for the multispectral bands and 81 cm per pixel for the Thermal infrared at a height of 120 m. Before and after the flights, a MicaSense Altum calibrated reflectance panel (CRP) was utilized to calibrate the sensor. These images were then radiometrically corrected based on the CRP images using Pix4Dfields 1.8.0 (Pix4d Inc., San Francisco, CA, USA). The CRP reflectance is used by the Pix4Dfields software in radiometrically correcting the image. The reflectance data were then used to compute vegetation indices for estimating the impact of the hailstorm on maize crop parameters (Table 1). These vegetation indices were selected based on their performance in the literature. The point data were overlaid with the images to extract spectral signatures, which were then used for the Random Forest regression analysis.

Statistical analysis

Random Forest was used to predict maize crop EWT, LAI and chlorophyll content before and after the hailstorm. RF was hyper-tuned by identifying the optimal estimation number of trees (*Ntree*), and predictor variables tested for the best split when growing trees (*Mtry*). To identify the *Ntree* and *Mtry* values that can best predict maize that best estimated EWT, LAI and chlorophyll content before and after the hailstorm, the Ntree (the default value is 500 trees) values were tested from 500 to 9500, while Mtry was tested from 1 to 25 using a single interval (Adam, Mutanga et al. 2012, Mutanga, Adam et al. 2012).

Accuracy assessment

To assess the EWT, LAI and chlorophyll model accuracies, the data were split into two datasets at a ratio of 70/30% for the training and testing datasets, respectively. The root mean squared error (RMSE), relative root mean squared error (RRMSE %), and the coefficient of determination (R^2) were computed and used to evaluate the magnitude of agreement between the predicted and field-measured data derived from each model.

RESULTS AND DISCUSSION

Before the hailstorm, EWT was estimated to a RMSE of 5.31 (rRMSE = 0.272 %) and R^2 of 0.88 based on the NDVI, NIR NDWI, ClGreen, NDVIrededge, in order of importance. A considerable decline in the estimation accuracies of maize EWT was observed after the hailstorm. Specifically, EWT was then estimated to an RMSE of 27.35 (rRMSE = 59.16) and R^2 of 0.65 based on NDRE, NIR, NDWI, Clrededge, NDVI red edge and red edge in order of importance (Fig. 1). Chlorophyll, on the other hand, was optimally estimated before and after the hailstorm. Chlorophyll was estimated to have a RMSE of 76.2 (rRMSE = 28%) and an R2 of 0.75 based on the NDVI, NIR, Red edge, CLred edge, and CCCI, respectively NDRE in order of importance and amongst other variables. An optimal estimation was attained again after the hailstorm with a RMSE of 31.3 and a R^2 of 0.78 (rRMSE =25%) with the Red edge, NIR, MCARI, OSAVI, ENDVI, CTVI being the most influential spectral features, in order of importance (Fig. 1). LAI was also optimally estimated before and after the hailstorm. Before the storm, LAI was estimated to a RMSE of 0.19 (rRMSE = 11%) and R^2 of 0.89 based on the modified nNDVI (NIR/Thermal), nNDVI (R/T), EVI2, GLI, nNDVI(R/Thermal), BNDIV as the most influential estimation spectral features, in order of importance. After the storm, a RMSE of 0.32 (rRMSE = 15 %) and R^2 of 0.91 was obtained based on the nNDVI (NIR/B), nNDVI (G/NIR), nNDVI(Thermal/NIR/), RBNDVI as the most influential spectral variables, arranged in order of importance (Fig. 1). Fig. 2 shows the spatial distribution of EWT, chlorophyll and LAI.

The hailstorm generally tears the leaves in some instances plucking them off. The leaves often begin to wilt at the edges, losing moisture and discolour. This alters the plant moisture content, LAI and chlorophyll content, and in some instances, functionality Red-edge is closely related to leaf moisture content, chlorophyll concentration and leaf area index. Canopy spectral reflectance in the NIR region is a function of water transmissivity and leaf internal structure and is strongly related to leaf moisture content (Ndlovu, Odindi et al. 2021). Meanwhile, when the plant is healthy, its cells will be turgid and full of moisture, highly photosynthesizing and producing more chlorophyll content sensitive to Red, Red Edge and NIR Thermal bands. Based on the study's findings, it can be concluded that the impact of hail damage can be optimally characterized through mapping EWT, Chlorophyll content, and LAI of maize using Red-edge, NIR, and Red-derived spectral variables.

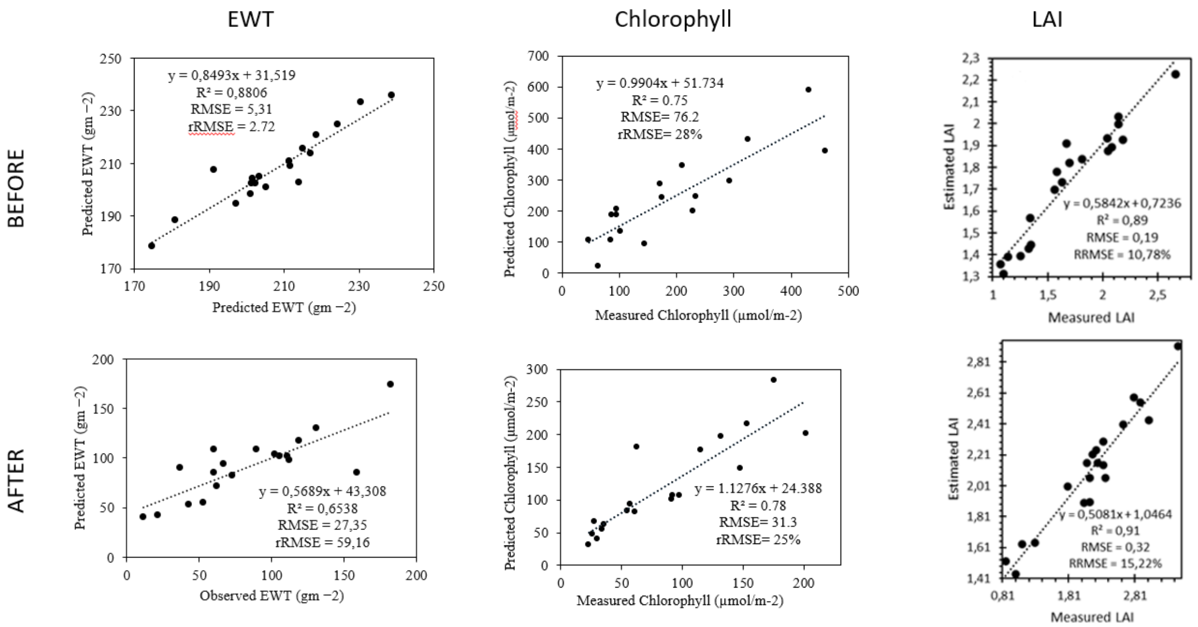

Fig. 1. One-to-one relation between predicted and measured EWT chlorophyll and LAI before and after the hailstorm.

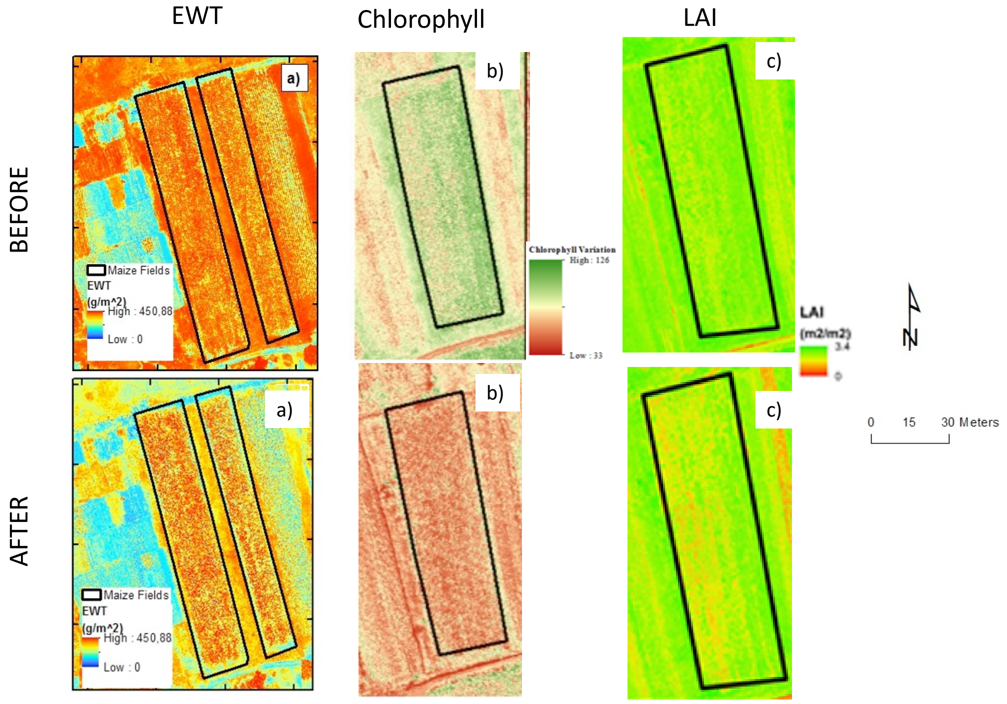

Fig. 2. The spatial distribution of EWT, chlorophyll and LAI before and after the hailstorm.

The implication of this Study's findings

There are high prospects of employing UAVs in crop condition assessment at the field scale. In interpreting the findings of this study there is a need to consider that this study was conducted based on data acquired after a hailstorm and in only one field. Subsequently, there is a need for further studies to investigate the contribution of site-specific factors in understanding the effect of natural disasters such as hailstorms on crops and the implications to yield.

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