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Research Paper

Application of thermal imaging of wheat crop canopy to estimate leaf area index under different moisture stress conditions

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Thermal imaging cameras determine the temperature of objects by non-contact measurements and give the temperature reading for each pixel of the image. They work on the same principle as spot pyrometers. Thermal imaging of the crop canopy can give the temperatures of both the crop canopy and the soil directly. However, a better distinction between the two classes, i.e., leaf and soil, can be made using image classification techniques. In the present study, thermal imaging was used to determine the canopy coverage of wheat; the leaf area index (LAI) was estimated under different moisture stress conditions. The thermal Images were analysed by five different supervised image classification techniques, maximum likelihood, Mahalanobis, minimum distance to mean, parallelepiped and support vector machine methods, using ENVI – image analysis software. The best estimation of LAI was by the support vector machine method, due to its higher overall classification accuracy and the Kappa coefficients. This was further supported by the statistical analysis based on the comparison between the digital image derived LAI and those measured using the plant canopy analyser. The LAI of wheat crop canopy estimated from the thermal images using the support vector machine method was meaningful with higher R^2 value of 0.915 and lower values of root mean squared errors (RMSE) and mean based errors (MBE). The present study clearly showed that thermal image analysis can be applied as a non-destructive, rapid technique to characterise the temperature of crop canopy and then to estimate the LAI of wheat grown under moisture stress conditions.

1. Introduction

Wheat (*Triticum aestivum*), which mainly originated in North Eastern Asia, is one of the widely cultivated cereals in the world. It ranks second (2.544 Mt) in terms of production just behind rice but ahead of maize. Wheat is a vital source of calories, and nearly 21% of the global population depends on wheat (FAO, 2016). Around 2.5 billion people in about 90 countries of the world are poor and are fed by wheat. Hence there is a need to improve the wheat crop production to feed the increasing global human population and to counter the climate change effects.

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The wheat crop is often challenged by biotic and abiotic stress factors. The maintenance of a good crop is an essential strategy for better production. Crop condition is regularly monitored in terms of the percentage of ground covered by healthy vegetation (Schirrmann et al., 2016). Thus, canopy coverage is the most important parameter that qualifies the dynamic crop growth rate. It also characterises the absorption fraction of photosynthetically active radiation (PAR) and the transpirational loss of water (Schirrmann, Hamdorf, Giebel, Dammer, & Garz, 2015; Tanaka et al., 2015).

Leaf area index (LAI) is defined as ratio of total one-sided leaf area to the ground area and it has a close correlation with the proportion of canopy coverage over the ground. LAI of crop determines the growth, fraction of absorbed PAR, biomass, and yield of crops. Thus, LAI is a key parameter for monitoring the crop status index (Banerjee, Krishnan, Das, Verma, & Varghese, 2015), LAI is used in crop yield prediction models (Krishnan et al., 2016), and hydrological and climate models (Waring & Landsberg, 2011). LAI is also needed for *in situ* crop growth monitoring and validating remote sensing products (Canisius, Fernandes, & Chen, 2010; Liu & Pattey, 2010; Liu et al., 2010). Hence, the accurate estimation of LAI is a necessity not only for better crop monitoring but also for its application in modelling and overall crop management (Wallach et al., 2001; Schirrmann et al., 2016).

Numerous techniques are available to estimate LAI, both by direct (destructive) and indirect (non-destructive) methods. The direct methods like computation of the leaf area of plant canopy require subsamples of leaves and subsequently LAI is related with dry biomass (specific leaf area, SLA). LAI is determined by multiplying SLA with total biomass by collecting remaining leaves that cover the specific ground area (Jonckheere et al., 2004). Though the direct measurement of LAI is the most accurate, this destructive method is expensive, time consuming and labour-intensive and is difficult for large scale application. Hence, indirect estimations of LAI are popular.

The plant canopy analyser is a widely used optical instrument for measuring LAI non-destructively (Liu, Pattey, & Admiral, 2013). The measurements are made through the amount of light intercepted by plant canopy which depends on the foliage density. The LAI can also be characterised through hemispherical imaging to estimate the gap fraction (Jonckheere et al., 2004). In this technique of hemispherical imaging, the percent ground cover of vegetation is assessed by pictures taken vertically and thereafter dividing the whole image into two well separable classes, i.e., the green and the non-green portions. Similarly, the estimation of canopy ground coverage by image analysis is widely accepted due to the availability of digital cameras with fine spatial resolution, high storage capacity, and lower price. The estimation of LAI through different image analysis techniques like thresholding of red, green, and blue colour based on the hue, lightness, and saturation, and the principle component analysis of red, green and blue colour has also been reported (Sudheer, Tejas, & JebaraniI, 2015). Many other optical techniques such as the Tracing Radiation and Architecture of Canopies (TRAC), SUNSCAN Canopy Analysis System (Dynamax, Inc.), and AccuPAR (Decagon Devices), work on the principle of gap fraction for estimating LAI indirectly (Zhao, Xie, Zhou, Jiang, & An, 2012). All these methods have proved that digital image analysis can be used to estimate the percent ground cover of the crop. However, the accuracy of estimation is affected by many factors including the sunlight condition. These methods have a strong subjectivity and frequent verification and interpretation by the operators make them quite unsatisfactory.

Thermal imaging is a promising technology for characterising crop conditions (Alchanatis et al., 2010; Jones et al., 2009). Two atmospheric windows, from 3 – 5 μm and 8–14 μm, allow the thermal imaging to visualise the differences in the surface in a non-invasive way, by sensing the infrared radiation emitted by it in relation to its temperature (Krishnan, 2014; Grant, Ochagavía, Baluja, Diago, & Tardáguila, 2016). Dutorchet in 1840 was the first to measure the temperature of a plant and its organs like leaves. Later, many studies have shown that the temperature of the plant canopy is different from its surrounding (Krishnan, 2014). The capabilities of thermography in monitoring soil salinity, crop water stress and the pest–crop-disease interaction, assessing the crop maturity, and estimation of crop yields have also been reported (Ishimwe, Abutaleb, & Ahmed, 2014). Proximal sensing of plant canopy by thermal imaging to derive LAI can be one of the most meaningful applications in precision agriculture. Hence the present study was undertaken to estimate LAI by thermal imaging of the wheat crop canopy under different moisture stress conditions and to compare these estimates using thermal and digital imaging with those measured from a plant canopy analyser.

2. Materials and methods

2.1. Study site and treatment details

Field experiments were carried out for two years (2014–15 and 2015–16) with wheat crops grown under different moisture stress conditions at the Indian Agricultural Research Institute, New Delhi (77°12′ E longitude, 28°35′ N latitude, and an altitude of 228.16 m over the mean sea level). The climate of the experimental site is semi-arid with dry, hot summer and dry winter. The crop season (*rabi*) was from mid-week of November to the first week of April. The soil at the experimental site is non-calcareous and slightly alkaline in nature, classified under the major group of Indo-Gangetic alluvium (Typic Haplustepts). The wheat cultivar HD 2967 was sown at 100 kg seed ha^{-1} at 20 cm row spacing under four different moisture stress treatments in three replications (3 (replication) × 4 (treatment) plots). The four moisture stress treatments (I1, I2, I3 and I4) were employed with different ratios of Irrigation Water/Cumulative Pan Evaporation (IW/CPE) of 1.0, 0.8, 0.6 and 0.4, respectively. The crop grown under the I1 treatment was under the optimum irrigation with irrigation condition at the crown root initiation (CRI), tillering, jointing, boot leaf, and flowering stages, which is recommended for the North-West plain zone of India. The crop grown under the I4 treatment was under the maximum moisture stress as it received only a single irrigation at the CRI stage. Analysis of Variance (ANOVA) under a Randomised Complete Block Design (RBCD) was used to assess the significant differences among various factors as well as their interactions.