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Georeferenced Ground Photography of Citrus Orchards to Estimate Yield and Plant Stress for Variable Rate Technology

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Citrus canopy measurements with ultrasonic and optical sensors are being used in Florida to control the placement and rate of fertilizers and pesticides with variable rate application (VRA) spreaders. A significant reduction of fertilizer or pesticide consumption is possible simply by applying agrochemicals only to orchard space occupied by trees with dense canopies. Additional refinement of agrochemical VRA may also be possible if fruit load (especially on alternate bearing trees), flowering intensity, and leaf nutrient stress could be measured on the tree canopies. Detection of early (mild) water stress before leaf wilting becomes visible and reduces yield, could be used to schedule irrigation, manipulate flower and leaf flushes, or improve fruit quality. In this study we developed ground-based digital photography systems to study the characteristics of citrus tree canopies over large areas. A color digital camera mounted on a moving vehicle was used to capture georeferenced overlapping images of tree canopies in entire orchards. Images were stored on a laptop computer and were processed using red–green–blue (RGB) pixel ratios and thresholds to identify and quantify numbers of mature fruit. A monochrome digital camera with visible and near-infrared bandpass filters was used to develop a multispectral imaging system capable of rapidly detecting early water stress in tree canopies. Significant correlations were achieved between the water stress index developed with the camera system and stem water potential measurements used for quantifying water stress in citrus trees. The water stress index could also detect, quantify, and map the severity of blight disease in orchard trees for an entire block.

Citrus canopy measurements with ultrasonic and optical sensors are being used in Florida to control the placement and rate of fertilizers and pesticides with variable rate application (VRA) equipment (Schumann et al., 2006a, 2006b, 2006c). VRA granular fertilizer spreaders are increasingly important for improving nutrient management efficiency in citrus orchards. A significant reduction of fertilizer or pesticide consumption is possible simply by applying agrochemicals only to orchard space occupied by trees (Zaman et al., 2005). Due to the rapid spread of two serious citrus diseases, citrus canker [*Xanthomonas axonopodis* pv. *citri* (*Xac*)] and citrus greening (*Candidatus* Liberobacter *asiaticus*) in Florida, there will be an increasing amount of tree removal and hence open ground interspersed by tree canopies in citrus orchards, thus making VRA increasingly important. The basis for most of the VRA of granular fertilizer or pesticide spray to Florida citrus orchards is the rapid detection and response to single tree sizes in real time (Cugati et al., 2007; Schumann et al., 2006a, 2006b, 2006c). Both ultrasonic and optical sensors currently in use make quantitative but not qualitative measurements of tree canopies. Such sensors, therefore, cannot discriminate between healthy and diseased trees. Consumption of agrochemicals could be further reduced if only healthy tree canopies were detected and treated, since materials applied to partially or completely defoliated diseased trees (which are still detected by ultrasonic or optical sensors) are often ineffective. Additional refinement of fertilizer VRA may also be possible if fruit load (especially in trees that are alternate bearing), flowering intensity, and leaf nutrient stress could be measured on the tree canopies and the agrochemical rates adjusted accordingly.

The existing method of monitoring and mapping manually harvested citrus fruit is based on recording the location of each filled fruit tub in the field using the geographic positioning system (GPS). Limitations of this system are that the fruit tubs are arbitrarily placed near the expected fruit picking locations between two rows, and there are an unknown number of trees contributing to the recorded yield in each tub. Thus, individual tree yields can never be established. The GPS coordinates for tubs are also usually triggered by the driver of the loading truck, which introduces substantial human error into the data. A more precise single-tree yield mapping system may be possible with the addition of yield sensors on mechanical harvesters or for manually harvested fruit, estimating yield on the tree before picking. Previous camera-based, non-destructive yield estimation of citrus produced mixed results. Most efforts focused on counting fruit numbers on the canopy images using machine vision algorithms (Annamalai et al., 2004; Chinchuluun and Lee, 2006) but the calibration R^2 with actual picked fruit yield was generally low (0.42 to 0.64). MacArthur et al. (2006) attempted to calibrate fruit pixel counts from color photos of tree canopies with fruit yield picked from the same trees. Their results were partially success-

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ful (best $R^2 = 0.373$) but failed to take into account the variable bearing volumes of three-dimensional tree canopies. Fruit yield in a citrus tree is a function of both fruit density or pixels per unit of two-dimensional canopy area seen in a canopy photograph, and also the three-dimensional canopy volume (Equation 1).

Yield = f(Fruit Pixels, Canopy Volume) [Eq. 1]

This equation should take into account the common situations where there are all possible combinations of high-yielding small trees and low-yielding large trees in the same orchard. A yield prediction system relying only on pixel or fruit counts can only be partially successful (Annamalai et al., 2004; Chinchuluun and Lee, 2006; MacArthur et al., 2006). When using only canopy volume, previous research by Zaman et al. (2006) achieved a calibration R^2 with yield of 0.80, using real-time ultrasonic sensors. In this present study, we attempted to synergistically combine both fruit pixels from digital cameras and canopy volume from ultrasonic sensors to obtain more accurate prediction of preharvest yields in the orchard.

Soil moisture sensors have so far yielded mixed results in automated citrus irrigation under Florida soil conditions. Most designs and technologies such as time-domain reflectometry (TDR) or capacitance sensors suffer from developing air gaps between the sensor wall and the soil particles. This is inevitable over time as roots grow around the sensors, the soil undergoes repeated wetting and drying cycles, and the surface tension forces of soil water loosen and move soil particles. Since all moisture sensors that measure dielectric properties of the soil medium have very restricted zones of measurement, any soil-sensor air gaps cause tremendous loss of sensitivity and calibration drift (e.g., capacitance, TDR probes). Tensiometers are even more vulnerable since they rely on intimate contact with the soil.

Microsprinkler or drip irrigation nozzles create notoriously uneven wetting patterns on sandy soils, and rainwater is unevenly distributed below the tree canopy due to stem flow and water shedding towards the canopy edge (Alva et al., 1999). Consequently, any soil water sensors placed in the wetted zone under a tree will produce unreliable results and thus make accurate irrigation scheduling impossible. Since the objective of all irrigation is to avoid drought stress in the plant, it seems logical to evaluate plant stress directly in order to schedule irrigation rather than to use indirect and unreliable measures of soil water availability.

Leaf wilting from advanced water stress is readily visible on tree canopies but should be avoided to prevent loss of yield. Detection of early (mild) water stress before wilting becomes visible and reduces yield, could be used to schedule irrigation, manipulate flower and leaf flushes, or improve fruit quality by increasing the soluble solids concentration. In addition, citrus diseases which affect the water balance of the tree could potentially be detected as water stress on the canopies. Thermal infrared (IR) cameras were used by Alchanatis et al. (2006) for early detection of water stress in grape vine canopies in irrigated vineyards. Unfortunately, leaf reflectance in the thermal infrared portion of the electromagnetic spectrum is subject to strong interference from air temperature, wind, and humidity (Alchanatis et al., 2006). Therefore, we explored the shorter wavelength near-infrared (NIR) range for canopy photography in this study since the interferences are less prominent.

The objective of this research was to determine the potential uses of georeferenced digital photography for citrus canopy measurements for use in VRA, yield prediction, water stress detection, and disease mapping.

Materials and Methods

1. Georeferenced digital color photography of citrus canopies for orchard inventory and yield prediction. A mobile camera system was mounted on a vertical aluminum mast attached to the back of a pickup truck (Fig. 1). The mast was designed to support two cameras at a height of 12 ft aboveground for photographing two adjacent rows of trees simultaneously, but in this prototype, only the right-hand side was implemented (Fig. 1). A Marlin F-146C2 digital camera (Allied Vision Technologies, Newburyport, MA) was mounted in a weatherproof fiberglass box on an adjustable bracket, which permitted selecting the optimum field of view (FOV) for oblique canopy photography according to the height of the trees and the row spacing. The camera was linked with a high-speed digital serial bus (IEEE1394) to a laptop computer located in the truck's cab. Customized Windows® software was used to display and adjust the live video, capture ground position information with a U.S. Coast Guard beacon differentially corrected GPS (DGPS) receiver, and synchronously trigger the storage of georeferenced canopy images based on the specified tree spacing (Fig. 2). Images were saved on the computer hard disk as compressed JPEG files, with the GPS coordinates embedded in the file name. GPS coordinates were first transformed from geographic to Universal Transverse Mercator (UTM) projection and were then offset by half a row spacing distance from the GPS antenna position to the tree row. The coordinates and additional data such as the ground speed, direction, time, and date stamps for each image were saved in a Microsoft Access® database file. Simple red–green–blue (RGB) pixel ratios of the image frame were used to preview and quantify the predominantly more red (fruit) portions and the greener, leafy canopy portions of the image. In a non-bearing tree, no ripe fruit were identified by this red enhancement, but the green foliage was identified (Fig. 2).

The ratios used were R/(R+G+B)*255, and G/(R+G+B)*255 for the red and green enhancement, respectively. Thresholds for each ratio were then adjusted in the software to achieve the desired discrimination between reddish fruit pixels and the remaining green pixels in each canopy image. The final result of percent fruit pixels in each tree canopy image was calculated

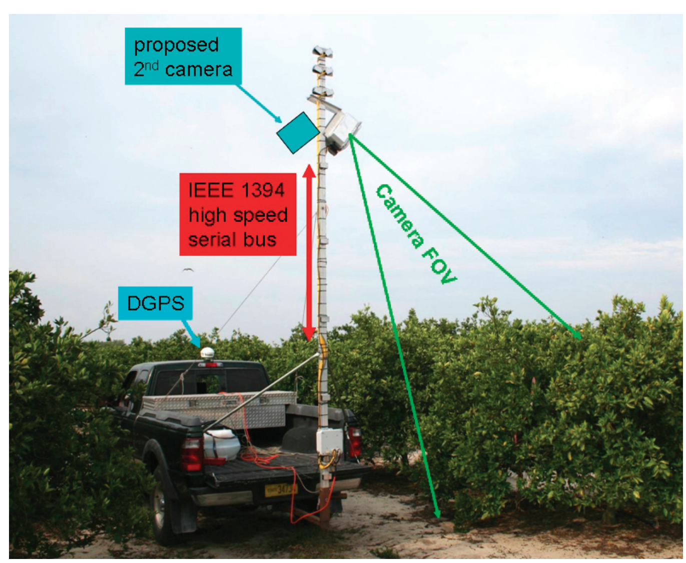

Fig. 1. Color camera system developed for taking real-time georeferenced canopy photographs.

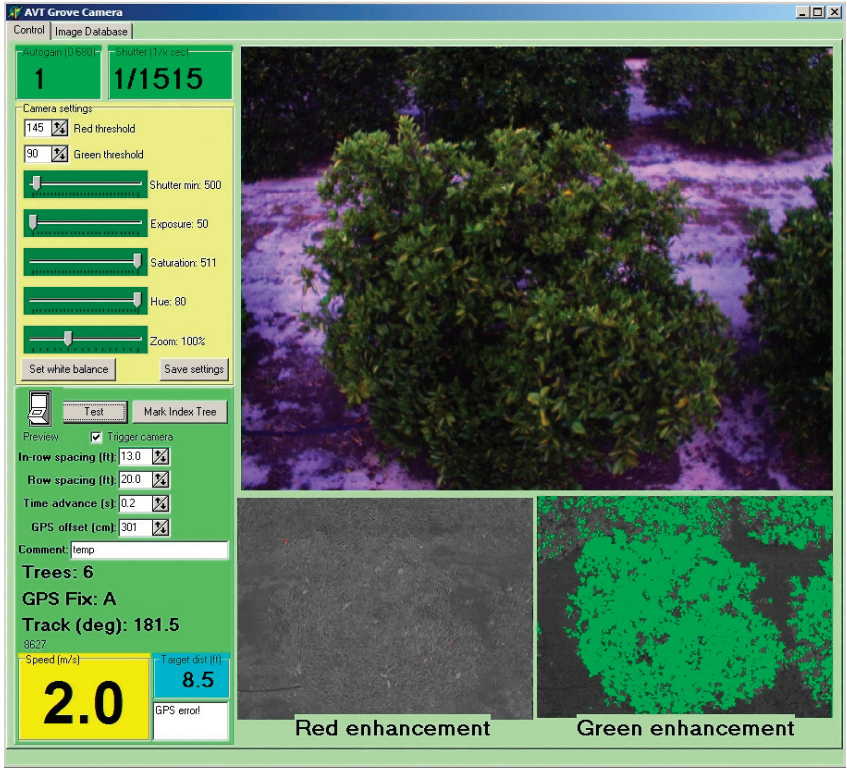

Fig. 2. Software console display on the laptop computer for the color camera system.

automatically in batch-mode and results were added to the database. In this study, two small blocks of 'Hamlin' orange [*Citrus sinensis* (L.) Osb.] on Swingle citrumelo [*Citrus paradisi* Macf. × *Poncirus trifoliata* (L.) Raf.] rootstock were used to test the camera system. The 774 fruit-bearing trees in 4.9 acres were photographed on 18 Jan. 2007 with the camera equipment at an average ground speed of 2.0 $m \cdot s^{-1}$ (4.5 mph). Both sides of the tree were photographed, yielding 1548 georeferenced color images that were batch-processed; the resulting percentage of visible fruit pixels were averaged for each tree. Canopy volume was also measured on both sides of each tree using an automated ultrasonic array and DGPS antenna (Schumann and Zaman, 2005), and then averaged for each tree using Arcview 3.2 GIS software (ESRI, Redlands, CA). For calibration purposes, a subset of 10 trees (five from each block) with a range of different yields were hand-harvested and the mature fruit per tree were weighed on an electronic field scale. A predictive yield index was calculated using a combination of both canopy volume (m^3/tree) and percent fruit pixels per tree canopy (Equation 2). For further validation, five trees of 'Valencia' orange [*Citrus sinensis* (L.) Osb.] on Swingle citrumelo rootstock from a nearby block were hand-harvested, photographed, and measured on 8 May 2007 to test against the 'Hamlin' calibration curve.

$$\textit{Yield Index} = (\textit{Fruit Pixels}\ \% \times \textit{Canopy Volume}) \qquad \text{[Eq. 2]}$$

The yield index and actual fruit yield data were analyzed by linear regression methods.

2. Georeferenced digital near-infrared photography of citrus canopies for water stress and disease detection. A multispectral camera with six selectable wavelengths in the visible and near-infrared region of the electromagnetic spectrum was assembled from a uEye (Imaging Development Systems, Cambridge, MA) monochrome video camera and a motorized filter wheel changer. The camera and filter selection wheel were controlled from a laptop computer using the USB-2 and RS-232 ports, respectively. Wavelength bandpass filters used were 450, 550, 670, 710, 840, and 970 nm. The camera system and computer were mounted on a golf cart for mobile use in the citrus orchard (Fig. 3).

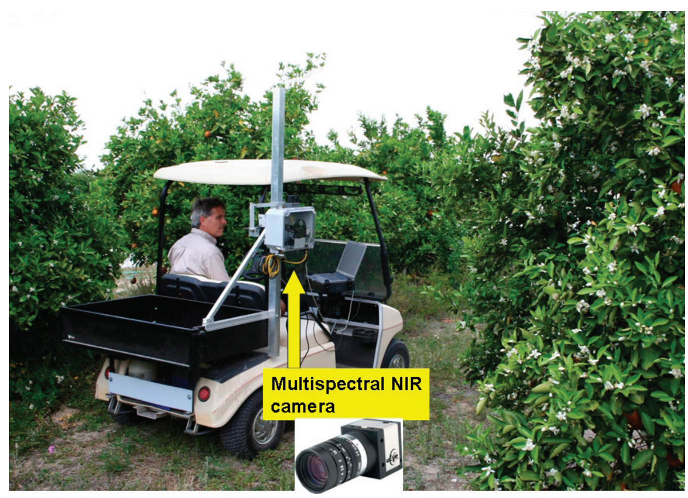

Fig. 3. Multispectral camera system mounted on the side of a golf cart.

During measurement of canopy reflectance, the camera was aimed from the cart in the row middle at the most sunlit portion of the tree canopy. Typical results of the six images at different wavelengths captured for each canopy scene are shown in Fig. 4. Only the sunlit leaves were selected for calculating the water stress index (Fig. 4) by using custom Windows® software and green pixel (550 nm) thresholds.

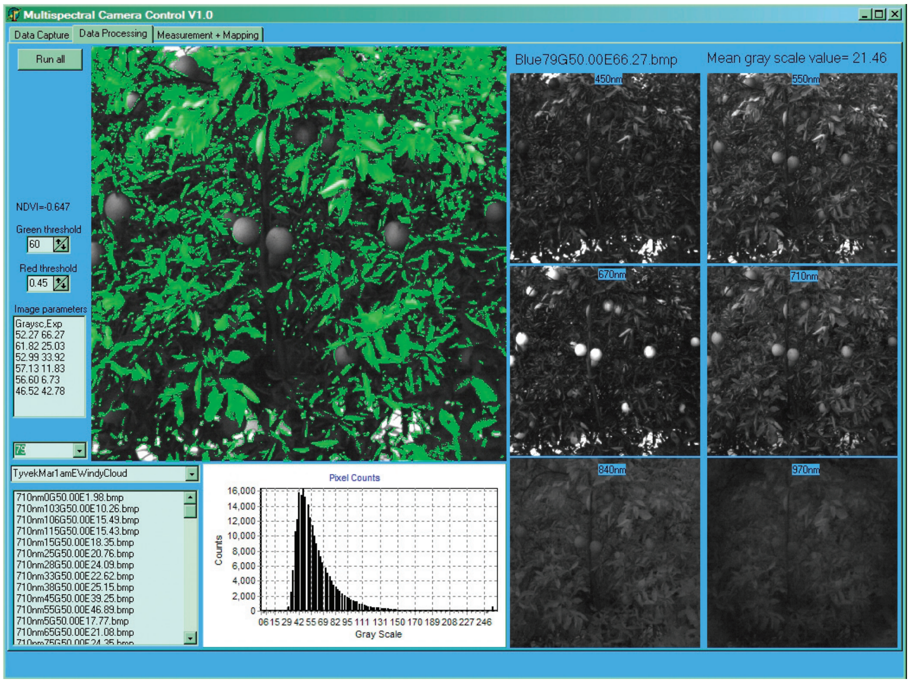

Fig. 4. Software console display on the laptop computer for the multispectral camera system.

The best ratio of wavelengths to use for the water stress index was determined by regressing various reflectance ratios at different wavelengths against reference stem water potential measurements taken on the same trees at the same time. For calibration, we used selected mature ‘Valencia’ orange trees on Swingle rootstock in an existing wintertime drought experiment under limited irrigation and Tyvek® covers (DuPont, Wilmington, DE) to exclude rain from the root zone. Treatments of water stress, listed from high to low in the experiment were 1) Tyvek cover, no irrigation; 2) Tyvek cover with occasional spot irrigation under the cover; 3) no cover, rain only, no irrigation; and 4) no cover, rain plus irrigation (control). On weekly measurement days, selected leaves were covered with foil and plastic bags in the early morning to equilibrate and were then picked near midday and measured with a pressure chamber apparatus to determine the stem water potential. For further work, the best canopy stress index (CSI, Equation 3) of wavelength ratios was selected by regression based on a simple reflectance (R) ratio:

$$CSI = R_{(840\ nm)}/R_{(670\ nm)} \qquad \text{[Eq. 3]}$$

A DGPS receiver and Microsoft Access database allowed the multispectral images to be georeferenced and stored on the hard disk of the laptop computer. Canopy stress indices could then be correctly mapped on Arcview 3.2. In order to evaluate the potential for the CSI to detect diseased canopies, 390 ‘Hamlin’ orange trees on Swingle rootstock in a 2.7-acre research block affected by variable amounts of citrus blight were photographed and mapped on one side with the multispectral camera and DGPS. Citrus blight is a wilt and decline disease of citrus whose cause has not been determined. The blight symptoms in this orchard consisted predominantly of variable levels of defoliation and upper canopy dieback, as well as a visible grayish cast to the foliage color. The georeferenced images and the derived CSI values were mapped with Arcview 3.2 in order to examine the spatial distribution of citrus blight in the orchard.

Results and Discussion

1. Georeferenced digital color photography of citrus canopies for orchard inventory and yield prediction. A sample georeferenced image of a ‘Hamlin’ orange tree with mature fruit taken with the color camera system is shown in Fig. 5. The photo was taken while the vehicle with the camera was moving past the tree at 2.63 $m \cdot s^{-1}$ (5.9 mph). Suitably high shutter speeds must be used in the camera settings in order to successfully freeze the motion without blurring. The system was subsequently tested at higher speeds up to 12 mph with similar good results, but driving through the orchard at such high speeds was not comfortable or safe.

After importing the georeferenced images and associated da-

Fig. 5. Single citrus canopy image captured by the color camera while moving at 2.63 $m \cdot s^{-1}$ (5 mph).

Fig 6. Result of using the hotlink tool of Arcview 3.2 to display georeferenced canopy photographs on an aerial photograph of the orchard.

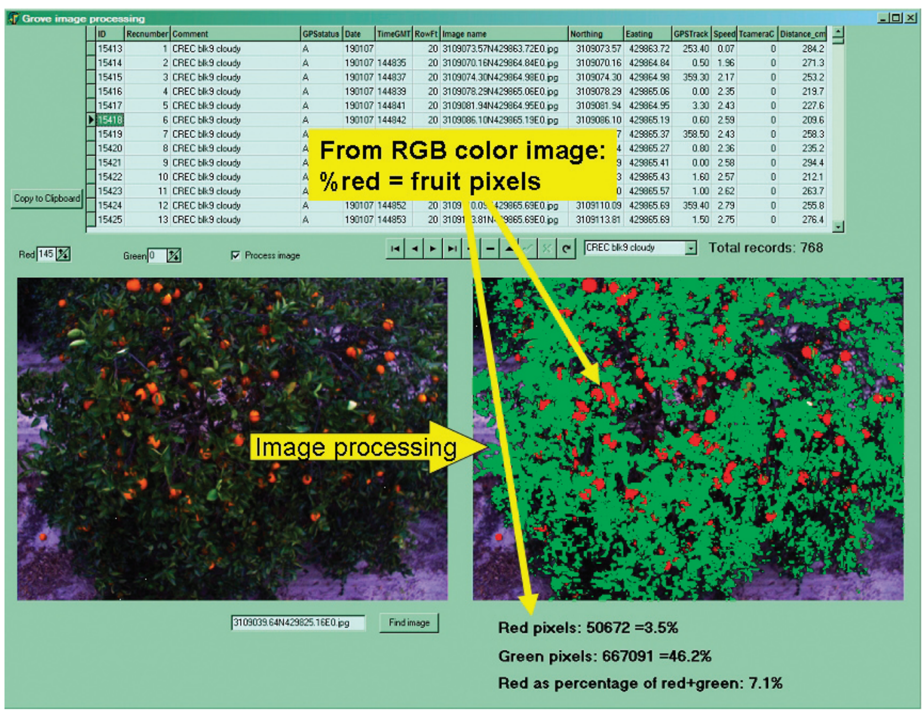

Fig. 7. Image processing technique used to enhance and count the fruit pixels on a canopy image.

tabase into the GIS, the position of each image could be shown on an aerial photograph of the 'Hamlin' orchard (Fig. 6). The different symbol colors for the north side of the tree (green) and south side (red) were automatically mapped by using the GPS direction information embedded in the database. The 'hotlink' feature of the GIS was then activated whereby the identity of each mapped canopy photograph point on the GIS was linked to the corresponding image file on the computer's hard disk. The hotlink feature was then used by clicking the mouse cursor on any image symbol on the screen, and the corresponding canopy image was displayed on the screen, as shown by the example in Fig. 6. The value of this GIS tool and the georeferenced canopy images is that detailed examination of the trees can be conducted at a later time, and permanent visual tree inventories for an entire orchard can be maintained on a computer.

Figure 7 illustrates the result of image processing a single tree canopy in order to obtain a mature fruit pixel count, expressed as a percentage of the whole canopy area. When only the fruit pixel percentages were compared with the actual fruit yield of the 10 harvested trees, a rather weak correlation ($R^2 = 0.60$; Fig. 8) was

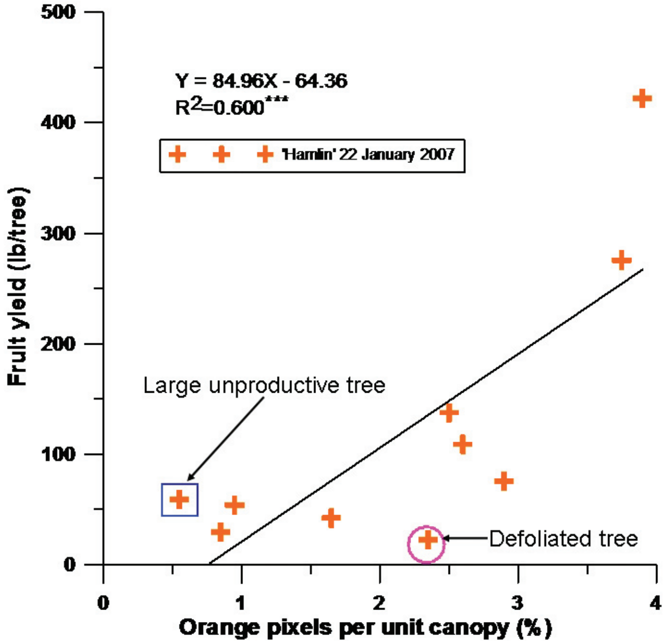

Fig. 8. Relationship between fruit yield per tree and the percentage fruit pixels on each tree canopy.

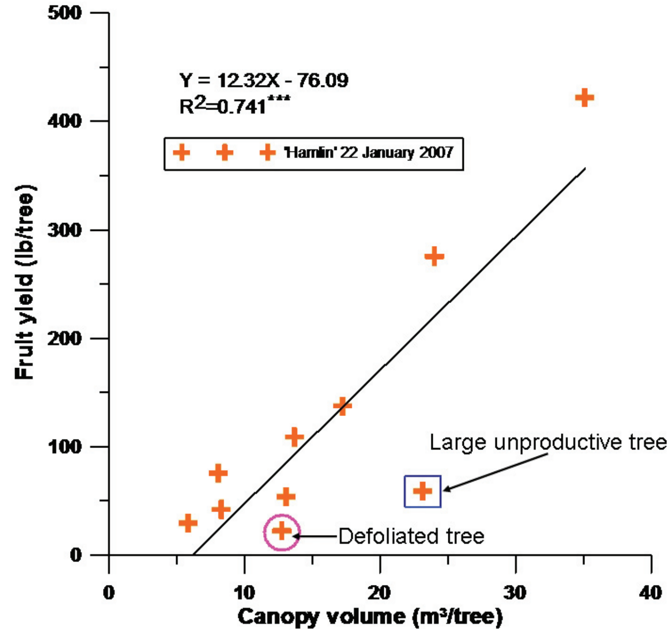

Fig. 9. Relationship between fruit yield per tree and the volume of each tree canopy.

obtained. This was not unexpected due to the incomplete yield information obtained from fruit pixels alone (MacArthur et al., 2006). Similarly, using only the canopy volume as a predictor of tree yield produced fairly weak correlations ($R^2 = 0.74$; Fig. 9) and agreed with similar studies by Zaman et al. (2006) who achieved an R^2 of 0.80. However, when both the fruit pixel and canopy volume information was combined using Equation 2, a very strong correlation with fruit yield was obtained ($R^2 = 0.997$; Fig. 10). To further illustrate the validity of this yield index, data from the five 'Valencia' orange trees harvested 4 months later were also plotted on the same regression graph with similar good results (Fig. 10).

A calibrated color camera, DGPS, and ultrasonic array could be used to estimate and map yield of ripe fruit in 'Hamlin' or 'Valencia' orchards. Unlike the harvesting tub yield logger attached to a "goat truck" that only maps fruit yield in broad regions of the orchard, this photographic method can estimate fruit yield of individual trees and therefore could be used for determining site-specific variable rate applications of agrochemicals.

2. Georeferenced digital near-infrared photography of citrus canopies for water stress and disease detection. There was a strong correlation between CSI derived from NIR (840 nm) and red light (670 nm) canopy reflectance and stem water potential of 'Valencia' oranges. Results for a clear day in February are shown in Fig. 11 ($R^2 = 0.34$).

The alignment of each treatment point on the regression line according to the level of water supplied was also as expected, where the driest treatment (Tyvek, no irrigation) had the lowest, most negative stem water potential and the highest CSI, and the wettest treatment (no cover, rain + irrigation) had the highest stem water potential and the lowest CSI (Fig. 11). Since most of the measured trees in the drought experiment were mature trees with large root systems, any impact of the water stress treatments was not yet visible in their canopies. However, a single smaller tree, a recent reset in the driest treatment, had visible leaf curl and wilt. Measurement of both stem water potential and CSI for that tree revealed that both parameters were still in a linear agreement with the previously measured data, but that CSI was much higher (about 28) and stem water potential was much lower (about –2.8 MPa, Fig. 12).

The CSI measurements of 390 'Hamlin' orange trees were interpolated by kriging in the GIS to produce a smoothed map of tree health in the 2.7-acre block (Fig. 13). The greener (or lighter gray) areas indicated the healthiest tree canopies, and the relatively red (or darker gray) areas were the trees most affected by decline,

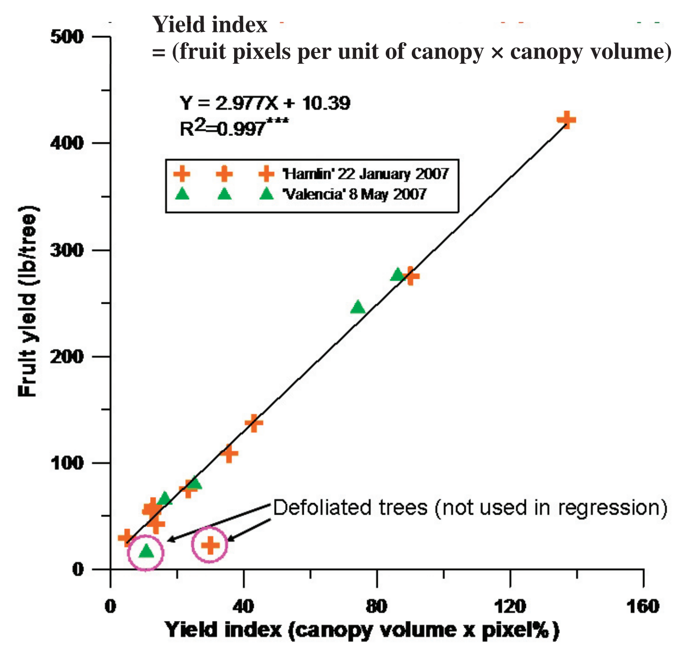

Fig. 10. Relationship between fruit yield per tree and the yield index calculated from percentage fruit pixels and canopy volume of each tree.

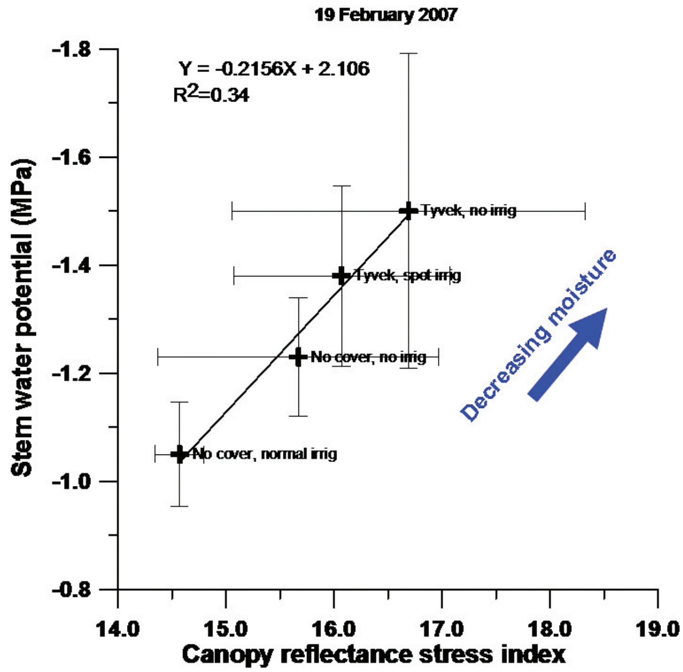

Fig. 11. Relationship between stem water potential and canopy stress index for mature 'Valencia' trees with different water stress treatments. Plotted points are the averages of three replications (±SE of both means) and the coefficient of determination (R^2) reflects the unaveraged data.

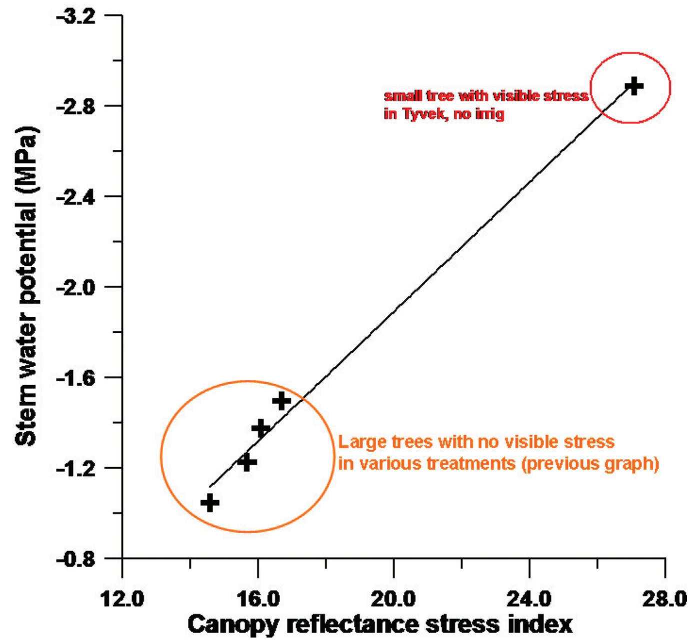

Fig. 12. Relationship between stem water potential and canopy stress index for mature 'Valencia' trees with different water stress treatments, including a single reset tree showing visible water stress.

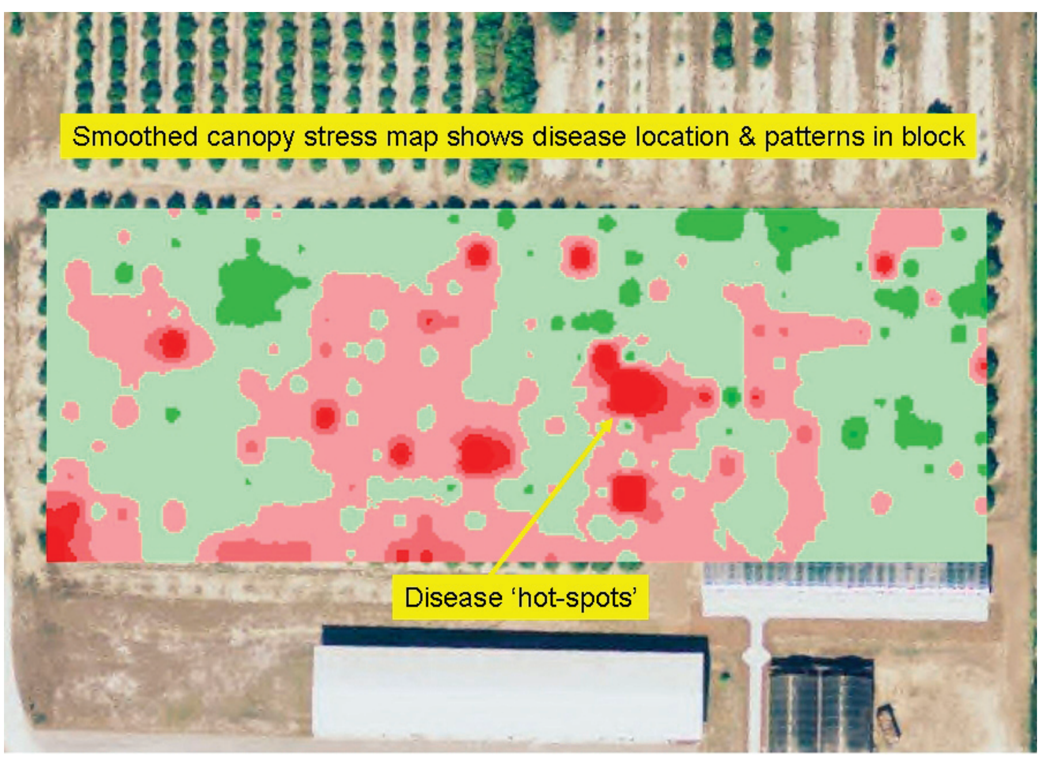

Fig. 13. Map of blight disease incidence inferred by CSI interpolated from the multispectral camera images of each tree canopy in the orchard. Red (or darker gray) zones indicate higher CSIs and greener (or lighter gray) zones indicate lower CSIs.

and in extreme cases were completely defoliated.

The repeated annual measurement of georeferenced CSI in this orchard could be useful for tracking the spread of diseases, and to investigate the causes of spatial patterns in disease severity. The CSIs calculated from digital images of trees in the near-infrared and visible portions of the electromagnetic spectrum may also have potential for detecting other more serious diseases such as citrus canker and citrus greening, but special precautions will have to be taken to avoid confounding the results of disease stress and water stress in the same trees.

Conclusions

•Georeferenced digital photographs of tree canopies can be collected in real time at speeds >6 mph in citrus orchards (up to 12 mph tested) using inexpensive cameras.

•Fruit yield of individual trees or any portion of canopy can be predicted accurately from a multiplicative index of canopy volume and fruit pixel counts.

•Near-infrared digital photography can be used to detect water stress in tree canopies and to detect canopy health.

•These photographic methods could be used to create digital orchard inventories, map yields and canopy damage from pests/diseases or wind, and to detect water stress from drought, flooding or salinity as well as to schedule irrigation and implement VRA of fertilizer and pesticides.

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