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Mapping interception of photosynthetically active radiation in sweet cherry orchards

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A B S T R A C T

Understanding interception of photosynthetically active radiation (PAR) of individual canopies could help advanced orchard management, thus, enhance fruit productivity and quality. The objective of this research was to develop a canopy PAR interception mapping method in Y-trellis trained sweet cherry orchards. A mobile measurement system was developed for continuously collecting constant spatial resolution PAR data at varying moving speeds. A mathematical model was developed to correct the distortion of the projected canopy shadow due to time of day and/or from orchard latitude. The mapping method was evaluated at both the dormant and full canopy stages. Digital images of 10 trees were used to validate the canopy projection correction method in each test. The measurement system achieved constant spatial resolution of 0.01 $m \cdot sample^{-1}$ within the entire platform speed range of 0–3.8 $km\ h^{-1}$. For dormant stage, the relative error in branch elevation angle comparison ranged from 0.1% to 9.6% with a mean of 3.4% ± 3.1%, and for full canopy stage, the relative error in canopy eccentricity ranged from 1.5% to 10.3% with a mean of 4.8% ± 2.6%. Combined, the results showed that the measurement system was capable of collecting high-density data with constant spatial resolution in orchards, and the canopy projection correction method can effectively correct the distortion in canopy maps caused by both imperfect sun zenith and azimuth angles at data collection. Light interception of individual tree canopies and the variation between/within canopies could be extracted from the corrected canopy maps, which should be useful for the advanced orchard management.

1. Introduction

The global tree fruit market is facing challenges of increasing competition and of the growing demand for higher quality fruit. Growers need to increase yield, improve quality, and decrease production costs to meet these challenges, which makes the adoption of advanced orchard management practices increasingly important. These may include, but are not limited to, technical planning, precision pruning, and improved insect and disease control. Photosynthetically active radiation (PAR) is the segment of incident radiation from 400 to 700 nm. In tree canopy, intercepted PAR is fundamentally important for photosynthetic organisms, because it stimulates the photosynthetic processes which in turn yield simple sugars and oxygen. A better understanding of PAR interception for individual tree canopies could help growers to improve their orchard management.

In the past decades, studies have revealed a positive relationship between midday canopy PAR interception and tree fruit productivity in conventional apple (*Malus domestica* Borkh.) and macadamia (*Macadamia integrifolia* Maiden and Betche) orchards (Jackson, 1980; Robinson and Lakso, 1991; Wagenmakers and Callesen, 1995; McFadyen et al., 2004). Measurements of PAR interception are based on tree canopies obstructing a fraction of incoming incident PAR from reaching the ground. The resulting canopy shadow is quantified and the difference between available PAR above the canopy and that reaching the orchard floor is referred to as canopy PAR interception. This shadow can also provide the 'blueprint' of a canopy. Giuliani et al. (2000) developed a light scanner to monitor the trees' shadow at different times within a day and demonstrated the potential value of canopy mapping based on PAR interception.

Numerous studies have investigated PAR interception for different crops. Different measurement techniques were compared in

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apple orchards, and fisheye photography and ceptometers were highly correlated to each other (Robinson and Lakso, 1989; Wünsche et al., 1995). Several types of photosensors were used in peach orchards and eggplant fields, such as Gallium Arsenide Phosphide (GaAsP) photosensors, linear PAR ceptometers and quantum sensors (Rosati et al., 2001; Rosati and DeJong, 2003; Grossman and DeJong, 1998; Castro and Fetcher, 1998). Giuliani et al. (2000) measured the PAR interception of a peach tree to generate the morphological traits of the canopy by using an array of 48 phototransistors topped by a Teflon layer as a diffuser. However, most of these methods were based on either hand-held devices or small-scale measurement systems, which were challenged when a large target area or short measurement time window was required. To solve this problem, Lampinen et al. (2012) developed a mobile platform, integrating a PAR measurement system, IR thermometers and a GPS unit on a utility vehicle, to conduct canopy PAR measurement in large acreage of almond and walnut orchards. However, their mobile measurement system recorded data at a preset constant rate which varied the data spatial resolution with respect to the platform traveling speed. As the distribution of leave density within a tree canopy is rather random, varying spatial resolution would make collected data represent canopy light interception less objective.

Modern, high density trellised orchard systems have been quickly adopted by tree fruit industry in Pacific Northwest Region of USA because of their advantage of efficient canopy design, uniform canopy architecture, and the ease of mechanizing operations. Large-scale PAR measurement in modern high density orchards will require high and consistent spatial resolution. To provide rapid and accurate PAR measurements, this study aimed to: (1) develop a mobile measurement system capable of continuously collecting PAR data in the field with a constant spatial resolution, (2) create a graphic interface for monitoring system working status in real-time, (3) develop an automated canopy mapping method capable of compensating the canopy footprint for geographical and sun position influences, and (4) validate the developed system via field tests.

2. Materials and methods

2.1. Mobile measurement system

To measure tree canopy PAR interception, a research prototype of a mobile PAR measurement system was designed and fabricated for this study (Zhang et al., 2012). This system consisted of two main subsystems, which were a mobile platform and a data collection system. The mobile platform was fitted to an Electric Gator (Deere & Company, Moline, IL), by attaching aluminum frames on which the sensors and a computerized data collection system were mounted (Fig. 1).

The key elements of the PAR measurement system included an integrated ceptometer unit (Item 1 in Fig. 1, AccuPAR LP-80, Decagon Devices, Pullman, WA, referred as the light-bar unit hereafter), a factory-calibrated Quantum sensor (Item 2 in Fig. 1, LI-190 SZ, LI-COR, Lincoln, NE), and an encoder (Item 5 in Fig. 1, TRD-S, Koyo Electronics Industries, Tokyo, Japan). The light-bar unit was constructed using a total of 80 independent photosensors, spaced at 0.01 m and grouped into eight, 10-photosensor units to output one cumulative reading from each unit in every reading cycle, which resulted in eight data points per sampling cycle. The Quantum sensor was used to measure the Photosynthetic Photon Flux Density (PPFD, unit μmol s^{-1} m^{-2}) under open sky conditions to provide a shadow-free reference radiation measurement. The encoder was used to measure platform moving speed for regulating the measurement system sampling rate.

Fig. 1. The mobile measurement system: (1) a light-bar, (2) a quantum sensor, (3) a signal input–output interface box, consisting of signal conditioning circuits and an NI DAQ module, (4) the E-Gator, and (5) an encoder, mounted on the rear wheel axle of the E-Gator.

The light-bars, Quantum sensor, and the encoder provided inputs to the system through a signal conditioning circuit which also converts sensor current outputs to voltage signals (Fig. 2(a)). A computerized data acquisition module, integrated by a NI cDAQ-9178 USB chassis, a NI 9205 analog input module and a NI 9401 digital I/O module, was used to acquire the sensed data.

The acquired signals were displayed on a laptop computer and recorded on the computer hard disk by using preinstalled NI LabView software (version 2010, National Instruments, Austin, TX). A bar chart in this virtual interface shows a graphical view of measured PAR signal intensity, and an analog odometer chart responsively presents platform moving speed (Fig. 2(b)). The interactive interface also allows users to record the start and stop time of one measurement by pressing the space key on keyboard.

2.2. Spatial resolution control

The spatial resolution of the PAR measurement system was defined as the physical distance between adjacent recorded data in the platform moving direction (along the tree row, defined as the *R*-axis hereafter) or perpendicular to the moving direction (across the inter-row spacing, defined as the *C*-axis hereafter). The 0.01 × 0.10 m physical dimension of each sensing unit resulted in a fixed spatial resolution of 0.01 m·$sample^{-1}$ in the *R*-axis and 0.10 m·$sample^{-1}$ in the *C*-axis for current light-bar arrangement as shown in Fig. 1. As the *C*-axis is perpendicular to the platform moving direction, the controllable spatial resolution discussed hereafter refers only to the one in the *R*-axis. Restricted by the dimensions of the sensing unit, the minimal achievable spatial resolution in *R*-axis would be 0.01 m $sample^{-1}$.

During field measurements, due to unpredictable field conditions such as uneven ground, the mobile platform was normally driven at a variable speed with frequent stops, which resulted in a variation in spatial resolution. To precisely measure canopy PAR interception, it was critical to maintain a constant spatial resolution. To accomplish this, a sampling rate control scheme was developed to dynamically control the sampling rate to respond to the changes in platform moving speed. Fig. 3 is a flowchart of the control scheme, in which the frequency reading from the encoder was used as the feedback signal to control the DAQ module sampling rate dynamically, synchronizing with the moving speed.

Based on this design, the *R*-axis spatial resolution (*R*, m $sample^{-1}$) is determined by the sampling rate (*S*, sample s^{-1}) and the platform traveling speed (*V*, m s^{-1}) using the following equation: