Characterization of canopy structure for high-yield performance of greenhouse-grown satsuma mandarins using direct measurements and indirect estimations

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Abstract

Under assuming that high-yield canopy structure would be simply explained by a given index, orchard productivity of greenhouse-grown early-flowering satsuma mandarins “Miyagawa wase” was assessed using conventional modified-open-center-training and trellis-training methods. This was done by using universal indices that assist with determining yield in relation to canopy structure. Leaf area index was the optimum index for determining fruit yield. Empirical extinction coefficients showed negative linear trends with yield. Either plant area index, estimated by using a plant canopy analyzer, and crown cover showed poor correlation with fruit yield. To effectively predict yield from leaf area index, a direct measurement is recommended rather than an indirect optical method. Trellis-trained trees were superior to modified-open-center-trained trees. This is because trellis-trained trees had higher fruit productivity up until 10 years old, and because 15-year-olds had better canopy light distribution patterns when compared with modified open-center-trained trees. Based on the costs associated with planting seedlings and the labor-efficiency due to width of free alley, trellis-training 2.2 m x 1.0 m plots was optimum for planting. In this study, even when accounting for the measurement error of woody elements, empirical extinction coefficients was a good index to base yield productivity. This is because this index directly represents vertical canopy light distribution. Additionally, the clumping index, calculated by using direct measurement and indirect optical method, was suggested to relate to canopy light distribution, however, further study must be essential.

Key words: Diffused light, Extinction coefficient, Fruit quality, Leaf area index, Training method

1. Introduction

Satsuma mandarin (Citrus unshiu Marcow.) is a major fruit crop sold year-round in local markets in Japan. From the months of September to March, satsuma mandarin fruits are produced in an open field, and from April to August, the fruits are produced by early-flowering satsuma mandarins grown in a heated greenhouse. The cultivation of greenhouse-grown early-flowering satsuma mandarins (hereafter referred to as “greenhouse-grown satsumas”) has several merits including a larger yield and higher trade price than those grown in open fields (Nii et al., 1984; Morinaga and Ikeda, 1991). In 2018, the cultivation area and fruit production of greenhouse-grown satsumas were estimated to be 400 ha and 20,000 t (5.0 t per 1,000 m²), respectively (Ministry of Agriculture, Forestry and Fisheries of Japan, 2019). However, both the area and amount of fruit produced have decreased since 1993. This is largely in response to high fuel requirements, lack of labor for cultivation—particularly harvesting—and yield limitations within conventional cultivation methods. To overcome these problems, the establishment of high-yield and low-labor cultivation methods is required. Such methods include reductions in fuel costs through various methods involving improving temperature controls (Yano et al., 2014).

Training systems used for fruit tree cultivation are critical factors in determining orchard productivity. When compared with deciduous fruit trees, there have been relatively few reports on training systems specifically targeted at optimizing citrus tree production (Morinaga et al., 1982; Ono et al., 1987; Rabe, 2000; Toyohuku et al., 2019; Kawasaki et al., 2020). A major training system used for citrus trees is the modified-open-center-training method, which is based on the natural tree form. The summary of this method is to form semispherical crowns with three main stems and to decrease plant density from 200–250 trees per 1,000 m² to 50 trees per 1,000 m² as an increment of canopy cover (Yakushiji, 1970). One of the reasons for the sparsity in available reports on these training systems is the requirement for a high degree of horticultural skill to manage the growth of the canopy (Robinson et al., 1991), which balancing vegetative—i.e., mother—shoots with reproductive—i.e., bearing—shoots. Specifically, this balance is important for satsumas cultivated under open field conditions, because the unbalance on amounts of mother and bearing shoots results in biennial cropping (Nishikawa et al., 2012). By contrast, shoot management among summer harvesting crop types is a much simpler process. Summer shoots that sprout by August are typically able to flower by December. This means that pruning was conducted immediately following fruit harvest in August,
resulting in no need to balance between mother and bearing shoot. This simple trait of summer harvesting crops is exceptionally advantageous when developing new training methods, especially when adapting methods for greenhouse cultivation. Based on summer harvesting, strong interference by pruning can be applied for maintenance and modification of trees when necessary.

In this study, to produce high yields with low-labor costs required for summer harvest cropping types of greenhouse-grown satsumas, the efficiency of shoot management was optimized. This efficiency was attempted although greenhouse-grown citrus fruits are known to have more active vegetative growth (Yano et al., 2018a, 2018b) and excessive tree vigor (Tachibana and Yahata, 2007) than citrus grown in open-field conditions. To account for and regulate tree vigor, a high-density trellis training system was tested that involved multiple leaders—i.e., three to four leaders per tree (Dorigoni and Micheli, 2014, 2015). However, the fruit productivity and effectiveness of this trellis-training system are still unknown, because of a lack of available research and data.

To determine orchard productivity, in this study, a select number of effective indices were recorded and reported. This action was made on the basis of previous fruit tree research that reported orchard productivity being determined through geometrical indices—such as tree density (Sansavini and Musacchi, 2002; Hampson et al., 2004; León et al., 2007; Robinson, 2007), canopy cover (Yakushiji, 1970; Ono et al., 1987; Tachibana and Nakai, 1989), canopy volume (Yakushiji, 1970), and canopy surface area (Yakushiji, 1970; Hutton, 1986). However, these indices were conducted on single straights and were thus too simple to be used to explain the universal productivity of fruit trees. This was true even when accounting for multiple growth training systems (Wünsche et al., 1996). Thus, more appropriate and universally applicable quantitative factors are required to effectively determine fruit tree parameters that specifically include factors such as canopy photosynthesis and/or dry matter production theory (Higashide, 2018; Nabeshima et al., 2019; Nomura et al., 2020).

Total dry matter production of a particular crop is described as a function of intercepted light—i.e., as a product of light use efficiency and intercepted light—(Scholberg et al., 2000; Higashide and Heuvelink, 2009; Higashide, 2018). The ability to intercept light by a crop is a function of the incident solar radiation on the plants, known as the leaf area index (LAI) and the light extinction coefficient (K). LAI is the main variable used for numerous biological process models, including photosynthesis and evapotranspiration. As the light extinction coefficient, K is based on Beer’s Law (Monsi and Saeki, 1953) and is a key index of canopy light distribution. Zhang et al. (2014) described how to interpret K as follows:

“a low K indicates that large amount of radiation can reach the bottom of the canopy, and conversely, a high K indicates that only a small amount of radiation can penetrate into the understory of the canopy.”

Theoretically, K is determined by leaf inclined angle and solar zenith angle (Monsi and Saeki, 1953; Campbell, 1986). When modeling canopy light interception, K = 0.5 is often used, which assumes a spherical leaf angle distribution (Green et al., 2003; Annandale et al., 2004). However, several previous reports have empirically shown K with a wide range (Kubota et al., 1994; Zhang et al., 2014). In relation to the empirically derived K, there are two main procedure categories used to estimate LAI: namely, direct measurement and indirect estimation methods (Jonckheere et al., 2004). Direct methods—such as leaf collection—are the most accurate; however, they require a large amount of effort (Jonckheere et al., 2004). By contrast, indirect methods—such as optical methods—are easier, but several reports have shown that they underestimate LAI when compared with direct measurements (Jonckheere et al., 2004; Weiss et al., 2004).

Several factors have been identified as possible sources for the underestimation of LAI in indirect methods. The first factor being clumping (Nilson, 1971; Bréda, 2003); Nilson (1971) defined the clumping index (Ω) as the nonrandom distribution of canopy elements (Bréda, 2003). When a canopy displays random dispersion, Ω is unity, whereas when a canopy has nonrandom dispersion, Ω is higher or lower than unity (Bréda, 2003; Chen et al., 2005). The more clumped a canopy is, the smaller the Ω value, and generally, most natural forest and shrub canopies are assumed to be clumped (Chen et al., 2005). The second factor is the contribution of stems and branches, where the indirect method measures all canopy elements intercepting radiation. This means that all canopy elements have often previously been defined as one plant area index (PAI), with PAI then being devided into LAI and wood area index (WAI; Bréda, 2003). Bréda (2003) illustrated that the WAI of oak stands ranged from 0.43 m² m⁻² to 2.45 m² m⁻², with the ratio of WAI to PAI further ranging from 7% to 40%. Thus, for an accurate estimation of LAI, a study requires the contributions from both clumping and woody parts to be determined (Bréda, 2003). Further to this, it is important to elucidate the relationship between orchard productivity and the contributions of clumping or woody elements.

The main objectives of this study were as follows: 1) to discover universal indices related to yield, beyond-the-site-specific, seasonal, and geometrical variations of tree canopy; 2) to compare orchard productivity with conventional modified-open-center-training and trellis-training methods; and 3) to discuss optimized planting and canopy structures for greenhouse-grown satsumas. To achieve these objectives, 16 greenhouses with varying tree ages—5–42 years old—were utilized. Fifteen of the selected greenhouses had modified-open-center-trained trees that were used to produce commercial fruits, with fruit productivity being assessed in one season from 2005 to 2006. The final greenhouse was operated with test treatments: four different spacing patterns for trellis-trained trees with multiple leaders, as well as a control treatment with modified-open-center-trained trees. Seasonal changes in fruit production among the test treatments were assessed over the long term, from 2 to 17 years of age, over a 15 year period from 2005 to 2020.

2. Materials and Methods

2.1 Plant materials and sites

Two types of training methods for greenhouse-grown “Miyagawa wasé” satsuma mandarins (Citrus unshiu Marcow.), grafted onto trifoliate orange [Poncirus trifoliatae (L.) Raf.] rootstocks, were tested. The first was a conventional modified-open-center-training method (Fig. 1a), with spacing
2.7–4.5 m (interrow spacing) × 1.4–4.4 m (intrarow spacing). Trees were planted in 15 greenhouses hereinafter referred to as “commercial trees”) located in Kutsuki, Oita, Japan. Greenhouses were heated from autumn to spring, and fruits were harvested from early June until early August. A summary of their cultivation is provided in Table 1. To minimize sampling error, four representative sample trees per greenhouse were selected. Generally, cultivation followed traditional practices, with the quantities of flower buds and fruit sets being sufficient to producing commercial fruits.

The second method was a trellis-training method with multiple leaders (Fig. 1b, Fig. 2), trialed in a test greenhouse in the Fruit Tree Group, Oita Prefectural Agriculture, Forestry, and Fisheries Research Center (33°32 ′ N; 131°43 ′ E, Kusisaki, Oita). The greenhouse was 33 m × 30 m in size, divided into five subfields (6.6 m × 30 m) using arches, roofed with 0.15-mm-thick polyester film, and walled off by 0.15-mm-thick vinyl sheets. To assess the seasonal change in productivity for the trellis-training with multiple leaders, 2-year-old satsuma mandarin seedlings were selected. Generally, cultivation followed traditional practices, their cultivation is provided in Table 1. To minimize sampling errors, the greenhouse was 33 m × 30 m in size, divided into five subfields (6.6 m × 30 m) using arches, roofed with 0.15-mm-thick polyester film, and walled off by 0.15-mm-thick vinyl sheets. To assess the seasonal change in productivity for the trellis-training with multiple leaders, 2-year-old satsuma mandarin seedlings were selected. Generally, cultivation followed traditional practices, their cultivation is provided in Table 1.

During the experimental years, the subfield was sandwiched on both sides by similarly cultivated subfields, which cultivated trellis-trained early-flowering satsuma mandarins (Fig. 3). These trees served only as “guard” trees (Nabeshima et al., 2019) to ensure that the experimental trees experienced a uniform microclimate and were consequently not sampled. All cultivation variables including air temperature and irrigation followed traditional practices (Tachibana and Yahata, 2007). During the experimental period, harvest days were conducted from June

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**Table 1.** Canopy dimensions, plant area index (PAI), leaf area index (LAI), wood area index (WAI), extinction coefficient $K$, and fruit productivity of commercial trees. WAI is shown if PAI > LAI.

| Planting | Tree age | Trees/1000 m² | Canopy dimensions | PAI ($m^2$) | LAI ($m^2$) | WAI ($m^2$) | $K$ | Average fruit size (g) | Fruit quality | Yield ($1000 m^2$) |
|----------|----------|----------------|-------------------|-------------|-------------|-------------|-----|-------------------|---------------|-----------------|
| 3.0 m × 2.3 m² | 8 | 136 | 2.7 | 62 | 0.7 | 2.9 | 2.0 | 0.9 | 1.72 | 94 | 11.1 | 0.65 | 5.8 |
| 3.0 m × 2.8 m | 8 | 121 | 2.7 | 63 | 0.2 | 2.8 | 2.0 | 0.8 | 1.75 | 97 | 9.9 | 0.82 | 6.2 |
| 3.0 m × 1.7 m | 9 | 157 | 2.2 | 72 | -0.1 | 3.7 | 2.7 | 1.1 | 1.32 | 97 | 12.0 | 0.74 | 4.7 |
| 3.0 m × 2.5 m | 9 | 110 | 2.7 | 48 | 0.4 | 3.5 | 1.4 | 2.1 | 1.92 | 78 | 11.1 | 0.69 | 4.9 |
| 3.0 m × 2.5 m | 10 | 110 | 2.4 | 41 | 0.2 | 2.9 | 1.4 | 1.5 | 2.05 | 88 | 11.6 | 0.86 | 4.0 |
| 3.0 m × 1.4 m | 12 | 181 | 2.4 | 77 | -0.1 | 3.3 | 2.1 | 1.3 | 1.62 | 100 | 12.4 | 0.61 | 7.0 |
| 3.0 m × 3.0 m | 12 | 113 | 2.6 | 62 | 0.4 | 3.8 | 2.1 | 1.7 | 1.49 | 93 | 13.0 | 0.85 | 4.9 |
| 3.0 m × 3.0 m | 12 | 100 | 2.3 | 67 | 0.1 | 3.7 | 2.0 | 1.7 | 1.60 | 75 | 12.5 | 0.74 | 4.3 |
| 2.7 m × 2.0 m | 20 | 150 | 2.1 | 74 | 0.0 | 4.2 | 1.8 | 2.4 | 2.48 | 100 | 11.9 | 0.91 | 6.3 |
| 3.0 m × 3.0 m | 28 | 120 | 2.8 | 89 | -0.1 | 3.6 | 2.2 | 1.4 | 1.57 | 80 | 12.3 | 0.72 | 5.7 |
| 4.5 m × 3.0 m | 40 | 72 | 2.7 | 90 | 0.5 | 3.5 | 1.8 | 1.7 | 1.49 | 110 | 11.0 | 0.76 | 6.6 |
| 3.8 m × 3.8 m | 42 | 75 | 2.7 | 87 | 0.0 | 3.3 | 2.4 | 0.9 | 1.16 | 111 | 12.1 | 0.72 | 6.7 |

* interrow spacing × intrarow spacing
8 to July 30 for all years, with flower buds and fruit sets were generally suitable for commercial fruit production.

2.2 Measurements

2.2.1 Plant area index

According to previous reports on forests and shrubs (Holst et al., 2004; Sano et al., 2012; Sun et al., 2020), PAI—including the contributions of leaf, stems, and branches—can be indirectly estimated using LAI-2000 (Li-Cor, Lincoln, Nebraska, USA). PAI measurements were conducted when there were diffused light conditions, such as on overcast days. The effect of steel frames—of roofs or sides of a greenhouse—on the LAI-2000 measurement was assumed to be negligible by the routine background correction.

The preliminary basic performance of the LAI-2000 for use with greenhouse-grown satsumas was confirmed in a leaf-thinning test conducted from June 2–6, 2005. The tested canopy, which was assumed to be closed, included two neighboring 11-year-old modified-open-center-trained trees. The whole canopy of the two trees was then divided into five vertical layers at 0.0–0.5, 0.5–1.0, 1.0–1.5, 1.5–2.0, and 2.0–2.5 m heights. Leaf-thinning tests were performed by alternating leaf collection from the vertical layers and LAI-2000 measurements in turn repeatedly. LAI-2000 performance was determined by comparing the leaf area for vertical layers with the LAI-2000 measurement. The test ignored stems and branches. To eliminate the effect of gap space—i.e., space outside the tree canopy—an optical sensor for the LAI-2000 was equipped with a 45° view cap. The LAI for the detached leaves was determined using the leaf area meter (LI-3000A; Li-Cor, Lincoln, Nebraska, USA). All LAI-2000 measurements performed well for the leaves ($r^2 = 0.88$, $P < 0.001$, $n = 44$; Fig. 4).

For commercial trees, the LAI-2000 measurements were taken beneath the canopy of each of the representative trees. Measurements were performed from November 2 to December 14, 2005. To collect information for the tree canopy on a wider scale, the optical sensor for the LAI-2000 was equipped with a 180° view cap. PAI data were averaged using 40–64 samples—measured at 0.5 m × 0.5 m grid-point inside tree canopy shilhouette area, with including at near the origin of stock—viewed equally from north, south, east, and west, for each greenhouse. For trellis-trained trees, it was assumed that the tree canopy was a row, and thus, the measurements were made in groups of diagonal transects, following the manufacturer instructions for the LAI-2000. PAI data were averaged over 30 samples—measured at point simmilar to commercial trees—with viewing occurring along each row for each plot. Measurements at 5 and 15 years old were performed October 17–23, 2007 and November 6, 2017, respectively.
2.2.2 Leaf area index

LAI was directly determined using either nondestructive or destructive methods. For the commercial trees and for the 5-year-old trellis-trained trees—including the control treatment—the LAI values were determined using a nondestructive method, which was conducted just before heating, from October to December. This method involved estimating the leaf area as a product of the number of leaves, by using a representative leaf area value for a single leaf. The values were estimated using a portable leaf area meter (LI-3000A; Li-Cor, Lincoln, Nebraska, USA), averaged over 400 leaves. LAI for the 10-year-old trellis-trained trees—including control treatment—was determined by a destructive method, which was conducted just after harvest. For this, leaf area was estimated as the product of the dry mass for all detached leaves from a single tree as well as the specific leaf area—established as $8.1 \times 10^{-3}$ m$^2$ g$^{-1}$ in a previous report (Yano et al., 2013). The LAI for the 15-year-old trellis-trained trees also used a destructive method, in which the leaves were detached from a tree and the leaf area was measured using a portable leaf area meter (LI-3000A; Li-Cor, Lincoln, Nebraska, USA). Measurements at 10 and 15 years old were performed August 1–31, 2013 and June 13–22, 2018, respectively.

2.2.3 Wood area index and clumping index ($\Omega$)

If PAI > LAI, it was assumed that the WAI could be estimated using the following formula:

$$\text{WAI} = \text{PAI} - \text{LAI}. \quad (1)$$

If PAI < LAI, it was assumed that the leaf distribution was clumped (Chen et al., 2005), and the clumping index ($\Omega$) could be estimated using the following formula:

$$\Omega = \frac{\text{PAI}}{\text{LAI}}. \quad (2)$$

2.2.4 Canopy light interception fraction

Light interception fraction ($\text{fIPPFD}$) was calculated using the following formula:

$$\text{fIPPFD} = 1 - \frac{\text{PPFD}_{\text{in}}}{\text{PPFD}_{\text{at}}} \quad (3)$$

where PPFD\text{in} is the incoming photosynthetic photon flux density (PPFD, µmol m$^{-2}$ s$^{-1}$) measured at a point between the ceiling of the greenhouse and the top of the tree canopy and PPFD\text{at} is the PPFD transmitted through the canopy. All the sensors used to measure the fIPPFD were fixed horizontally to the ground. Measurements were performed from November to December.

Measurement instruments were selected on the basis of canopy type. First, for commercial trees and for 5-year-old trellis-trained trees—including control treatment—two-point PPFD sensors (LI190SA; Li-Cor Inc.) were used that were connected to the LAI-2070 control unit of the LAI-2000. One PPFD sensor was mounted to a treetop, with another mounted to the side of the LAI-2050 optical sensor. The instantaneous PPFD data were collected by the LAI-2070 control unit. Thus, measurement point for the fIPPFD data corresponded to that for the PAI data. Second, for the 15-year-old trellis-trained trees, assuming that there was a row canopy, a PPFD bar made from a 2 m aluminum bar and six PPFD sensors (MU-14PAR Type2/K2; Environmental Measurement Japan, Co., Ltd.) evenly spaced along the bar were used. The PPFD bar was designed as a substitute for a line–PPFD sensor, and the PPFD bar could be hung in the greenhouse. The PPFD bar was placed perpendicular to the rows. Instantaneous light interception was obtained using one set of the alternate PPFD\text{at} measurements at the top of the canopy and for the PPFD\text{in} just below the canopy. Each measurement spanned 3–5 min, with measurements taken at 5 s intervals. By using either measurement instrument, the instantaneous fIPPFD was measured on overcast days during the off-crop season at the preflowering growth stage.

2.2.5 Canopy light extinction coefficient ($K$)

Despite the training methods, the light extinction coefficient, $K$, was empirically derived using the classic exponential formulation to modify Beer’s Law (Monsi and Saeki, 1953):

$$K = -\frac{\ln (1 - \text{fIPPFD})}{\text{LAI}} \quad (4)$$

where fIPPFD is the fraction of light interception calculated by Equation 3. Measurements were performed from November to December. LAI was determined by the methods aforementioned at 2.2.2, with assuming that LAIs before heating and after harvest have no difference in greenhouse-grown satsumas.

2.2.6 Geometrical canopy description

Canopy geometry of modified-open-center-trained trees—including tree height—was assumed as a discontinuous hemisphere; an average of the horizontal crown radius was determined by the maximum among tree crown radiiuses measured at heights of 0, 0.5, 1.0, 1.5, 2.0, and 2.5 m. Canopy cover was determined by using the average of horizontal radius, following methods described in previous studies (Yakushiji, 1970; Tachibana and Nakai, 1989). Free alley width was determined by a deduction of the average planting distance and average horizontal radius. For commercial trees, canopy geometry was estimated by using four representative sample trees per greenhouse.
Canopy geometry of trellis-trained trees—including tree height—was assumed as a continuous canopy like with a triangle prism; thus, the canopy cover and free alley width were determined by using the product of canopy width and length, and a deduction of the average of planting distance and canopy width, respectively. For trellis-trained trees, canopy geometry was estimated by using all sample trees.

Measurements for both modified-open-center-trained and trellis-trained trees were performed from November to December.

2.2.7 Other indices

Duration of sunshine (h) from January to June 2006 for commercial trees was estimated using AMEDAS data for Kitsuki (Oita, Japan). Duration of sunshine (h) and solar radiation (Rs, MJ m$^{-2}$) from January to June 2008–2020 for trellis-trained trees were estimated using meteorological observation system (M-801; Yokogawa Electric Corp., Japan) in the Fruit Tree Group, Oita Prefectural Agriculture, Forestry, and Fisheries Research Center (33°32′ N; 131°43′ E, Kunisaki, Oita). Both of duration of sunshine and solar radiation were directly estimated by using raw data of the AMEDAS or meteorological observation system. Yields were estimated by using data with four representative sample trees per greenhouse for commercial trees and by using data with all sampled trees in Fig. 3 for trellis-trained trees, respectively. Soluble sugar content (SSC) for juice produced by cultivated fruits was measured with a digital refractometer (PR-101, ATAGO Co., Ltd.). Acidity of the fruit juice was measured through titration. SSC, acidity of the fruit juice, and fruit weight were sampled at harvest peak day, which generally corresponded to from early June to early August. Data analysis was performed using R-3.6.1 (R Development Core Team, 2019).

2.2.8 Variation in sites and research years

Generally, cultivation in the commercial trees and the trellis-trained trees followed traditionally observed practices. However, light conditions fluctuated somewhat between year and site. The seasonal sum for the duration of sunshine from January to June was 18% larger in Kunisaki City for trellis-trained trees than in Kitsuki City for commercial trees (Table 2). Consequently, the trellis-trained trees received slightly better light for fruit production than the commercial trees.

#### Table 2. Duration of sunshine (h) in the Japanese cities of Kitsuki and Kunisaki during the experimental period included active fruit growth periods.

| Month | Kitsuki 2006 | Kunisaki 2008–2018 |
|-------|--------------|---------------------|
| Jan   | 140          | 136 ± 17$^2$        |
| Feb   | 125          | 146 ± 23            |
| Mar   | 190          | 191 ± 22            |
| Apr   | 161          | 194 ± 28            |
| May   | 122          | 206 ± 25            |
| Jun   | 105          | 123 ± 26            |
| Sum   | 843          | –                   |
| Mean of sum | –     | 996 ± 75           |
| Maximum of sum | –     | 1,105              |
| Minimum of sum | –     | 878               |

$^2$ Means ± SD

3. Results

3.1 Productivity of commercial trees

A summary of the commercial satsuma mandarin trees assessed is presented in Table 1. The average of fruit weight was at ~90 g, with SSC at ~12 °Brix, and the acidity at ~0.8%. These values met the general commercial requirements for satsuma mandarin fruits in Japan. With conventional shoot management—where stems and branches were spread horizontally—almost all greenhouses had narrow free alley widths (0.2 ± 0.05 m; Table 1). The maximum yield and LAI were 7.6 t per 1,000 m$^2$ and 3.6 m$^2$ m$^{-2}$, respectively. Tree height ranged from 2.1 to 2.8 m.

3.2 Productivity of trellis-trained trees

A summary of the productivity of the satsuma mandarin trellis-trained trees is shown in Table 3 and Figure 5. Until 10 years of age, fruit yield was proportional to the planting density with a logarithmic trend (Fig. 5), in which some factors or single factor can fluctuate the yield. For example, for the 6- to 8-year-old trees, an unplanned water deficiency due to a lack of irrigation resulted in underestimations of the fruit yield, as shown

#### Table 3. Canopy dimensions, plant area index (PAI), leaf area index (LAI), wood area index (WAI), and extinction coefficient $K$ of the trellis-trained trees. WAI is shown if PAI > LAI.

| Treatment        | Planting | Tree age | Trees/1000 m$^2$ | Canopy dimensions | PAI (m$^2$ m$^{-2}$) | LAI (m$^2$ m$^{-2}$) | WAI (m$^2$ m$^{-2}$) | $K$ |
|------------------|----------|----------|------------------|-------------------|----------------------|----------------------|----------------------|-----|
| Trellis training | 2.2 m×1.0 m$^2$ | 5        | 390              | 2.7               | 80                   | 0.5                  | 3.4                  | 0.8 | 2.6 | 4.58 |
|                  | 2.2 m×1.5 m$^2$ | 5        | 283              | 2.7               | 78                   | 0.5                  | 2.7                  | 0.5 | 2.2 | 6.35 |
|                  | 1.6 m×1.0 m$^2$ | 5        | 558              | 2.6               | 85                   | 0.2                  | 2.9                  | 1.4 | 1.5 | 1.89 |
|                  | 1.6 m×1.5 m$^2$ | 5        | 378              | 2.6               | 88                   | 0.2                  | 2.7                  | 1.2 | 1.4 | 2.69 |
| Control          | 2.2 m×2.0 m$^2$ | 5        | 207              | 2.3               | 65                   | 0.1                  | 2.5                  | 1.0 | 1.6 | 2.86 |
| Trellis training | 1.6 m×1.0 m$^2$ | 10       | 558              | 2.7               | –                    | –                    | –                    | 4.1 | –   | –   |
|                  | 1.6 m×1.5 m$^2$ | 10       | 378              | 2.7               | –                    | –                    | –                    | 3.5 | –   | –   |
| Control          | 3.6 m×2.8 m$^2$ | 10       | 104              | 2.3               | –                    | –                    | –                    | 1.1 | –   | –   |
| Trellis training | 2.2 m×1.0 m$^2$ | 15       | 390              | 2.7               | 59                   | 0.8                  | 3.4                  | 4.1 | –   | 0.51 |
|                  | 2.2 m×1.5 m$^2$ | 15       | 283              | 2.7               | 59                   | 0.9                  | 2.7                  | 3.8 | –   | 0.49 |

$^a$ interrow spacing × intrarow spacing
by the high SSC values and small fruit sizes (Fig. 6a–c). However, overall, fruit productivity for the trellis-trained trees mainly followed LAI (Fig. 6a and 6e), and a tendency of biennial fruiting was not recognized (Fig. 6a). Five-year-old trees had a narrow free alley width of 0.5 m or less, although 15-year-old trees had a wide free alley width of 0.8–0.9 m (Table 3). The wide free alley was obtained by training and trimming tree canopy. Tree height ranged from 2.3 to 2.7 m (Table 3). Additionally, during the experimental years, solar radiation ($R_s$) from January to June only affected acidity, although it did not show a significant correlation to the other indices of fruit production (Table 4).

3.3 Comparison of indices affecting yield

During experimental years, $R_s$ did not show a significant correlation to fruit yields, by using averaging data of trellis-training 2.2 m × 1.0 m and 2.2 m × 1.5 m (Table 4). The reason for using the averaging data was to grasp general effect of environment on fruit productivity. Additionally, both of the trellis-training 2.2 m × 1.0 m and 2.2 m × 1.5 m showed similar results (data not shown).

LAI showed a significant positive correlation with fruit yield, with a similar pattern for both trellis-trained and modified-open-center trees (Fig. 7b). To assess the differences or correspondence of the linear trends of LAI with yields for trellis-trained and modified-open-center trees, the slopes and intercepts of the linear models were compared using an analysis of covariance. The slopes of the two regression lines (Fig. 7b) were not significantly different ($P = 0.60$), with the trees of the two training methods having a common intercept in the regression line ($P = 0.16$). Therefore, a relationship between LAI and yield could be simply described using a common regression line for both training methods. Thus, yield ($Y, t$ per 1,000 m$^2$) can be modeled by the following formula, and the model explained 72% of the variation of yield.

$$Y = 1.56 \text{ LAI} + 2.16 \quad (n = 27, R^2 = 0.72, P < 0.001) \quad (5)$$

The extinction coefficient $K$ showed a significant negative correlation with fruit yield; however, there was a slightly different pattern between the trees from the two training methods (Fig. 7c). The slopes of the two regression lines (Fig. 7c) were not significantly different ($P = 0.075$), and the trees of the two training methods had a common intercept in the regression line ($P = 0.96$). Thus, yield $Y$ can be modeled by the following formula, and the model explained 47% of the variation of yield.

$$Y = -0.91K + 7.15 \quad (n = 22, R^2 = 0.47, P < 0.001) \quad (6)$$

Both the PAI and canopy cover showed a poor correlation than LAI with fruit yield (Fig. 7a and 7d).

3.4 Light interception pattern and canopy structure

To characterize the canopy structure of greenhouse-grown satsumas, a comprehensive investigation was conducted on
Fig. 7. Comparison between trellis-training method and modified-open-center-training method (control and commercial trees) for the relationship of fruit yields against (a) plant area index (PAI), (b) leaf area index (LAI), (c) extinction coefficient $K$, and (d) canopy cover. Solid line and dotted line indicate the regression line ($P < 0.05$) for the trellis-training method and the modified-open-center-training method, respectively. Number shows tree age.

Table 4. Correlation between solar radiation ($R_s$, MJ m$^{-2}$) from January to June and indices of fruit production in trellis-trained trees (average data of trellis training 2.2 m × 1.0 m and 2.2 m × 1.5 m) from 2008 to 2020 ($n = 12$).

|                          | $r$   | $P$  |
|--------------------------|-------|------|
| Average fruit size (g)   | 0.39  | 0.21 |
| SSC (° Brix)             | 0.44  | 0.13 |
| Acidity (%)              | 0.73  | 0.007|
| Yield/1,000 m$^2$ (t)    | -0.38 | 0.22 |

several canopy features. The light interception fraction ($f_{IPPFD}$) was over 0.8 and was near constant when compared against LAI (Fig. 8a). The relationship between LAI and the empirically derived extinction coefficient $K$ showed a negative trend, in which a nonlinear pattern can be fitted (Fig. 8b). $K$ increased with the ratio of WAI to PAI (Fig. 9). Furthermore, when PAI > LAI with a clumping index $\Omega > 1$—which included trees from the modified-open-center-training method as well as the 5-year-old trellis-training method—the $K$ values were high at over 1.0 (Table 1 and 3). Another situation in which PAI < LAI and the clumping index $\Omega < 1$, was with the 15-year-old trellis-trained trees, where $K$ was close to 0.5 (Table 3). The different trends for the indices suggest a change in the canopy architecture for the greenhouse-grown satsumas.

4. Discussion

Overall, in greenhouse-grown satsumas, results showed usefulness of selected indices for explaining fruit yields, and of trellis-training method for high-yield. In this section, three objectives, which were mentioned at introduction, and one subject, which requires further study on characterizing detailed canopy structure, were discussed.

4.1 Universal indices related to yield

In trellis-trained greenhouse-grown satsumas, solar radiation from January to June did not show a significant correlation to fruit yield (Table 4). Taniguchi (1983) showed that combination of 95% shading and high air temperature above 25°C from flowering to the end of June-drop term affected fruit set. In the present study, from January to February, air temperature was conventionally controlled less than 25°C, and difference of solar radiation among plots was not the level as affecting fruit set (Table 2). After the June-drop term, previous reports on modified-open-center-trained trees reveal that 60% shading from March to May did not show significant differences in the yield compared with trees with no shading (Yano et al., 2013). In the present study, the whole fluctuation level of sunshine duration from January to June was at most 30% (Table 2). Therefore, this fluctuation level of sunshine duration was not assumed as a factor affecting yield.

LAI correlated linearly with fruit yield (Fig. 7b). Analysis of covariance revealed that fruit yield was explained by LAI with a linear regression line, regardless of the training used for the trees.
Effect of leaf area index (LAI) on the light interception fraction (fIPPFD) and the extinction coefficient K. Number shows tree age.

Thus, LAI was suggested to be a universal index related to yield at least LAI<4.0 m² m⁻². These results coincide with previous reports for the modified-open-center-training method (Yakushiji 1970; Ono et al., 1987; Tachibana and Yahata, 2007) and natural tree forms (Tachibana and Nakai, 1989). However, the present study measurement method for LAI—such as leaf collection or leaf counting—required destructive sampling or a significant amount of effort. For an effortless and practical estimation of LAI, other direct or indirect methods must be established, such as allometric techniques (Jonckheer et al., 2004).

Extinction coefficient K also showed a significant correlation with fruit yield (Fig. 7c). Similar to LAI, analysis of covariance revealed that the fruit yield was explained by K with a linear regression line, regardless of the training used for the trees (Fig. 7c). However, the model explained the lower variation of yield rather than that of LAI, thereby inferring that the extinction coefficient K was a secondary effective index related to yield. Furthermore, the relationship between K and fruit yield may be spurious correlation, because K and LAI showed a significant correlation (Fig. 8b).

The PAI determined by the LAI-2000 showed a narrower range than the LAI and poor correlation against the fruit yield (Fig. 7a). In this study, it was assumed that the poor correlation was mainly due to an error in the information calculated for the stems and branches and thus calculated a WAI using Equation 1. Bréda (2003) questioned whether the PAI equals the sum of LAI and WAI (Lang, 1991; Chen, 1996) or this equality is not a general assumption because of the overlapping of branches by leaves (Dufrêne and Bréda, 1995; Gower et al., 1999). Through this study, estimation on WAI were made according to Lang (1991) and Chen (1996). Therefore, close attention must be paid to the measurement error when using an indirect method, for example, PAI is constructed with at least two different measurement elements.

Canopy cover did not show a universal relationship against yield (Fig. 7d). The reasoning for this was different for each training method. First, in trellis-trained trees, 5-year-old trees with wide canopy width (large canopy cover) and low LAI resulted in low fruit yields (Table 3, Fig. 7b). Conversely, 15-year-old trees with narrow canopy width (small canopy cover) and high LAI resulted in high fruit yields (Table 3, Fig. 7b). Thus, the relationship in trellis-trained trees between canopy cover and yield showed a negative trend (Fig. 7d). Second, in the modified-open-center-trained trees, canopy cover and yield did not show a significant correlation (Fig. 7d). In the open field, Ono et al. (1987) highlighted that yield fluctuation among sites increased when both canopy cover and LAI were over 60% and 2.5 m² m⁻², respectively. In this study, the most canopy cover recorded was over 60% (Table 1); thus, a worse canopy light distribution originating from a horizontal crown spread might partly cause yield fluctuation. Therefore, canopy cover is simply too one-dimensional to accurately describe the yield of greenhouse-grown satsumas.

4.2 Orchard productivity of modified-open-center-training and trellis-training methods

Through this study, it was concluded that trellis-trained trees were superior to modified-open-center-trained trees. The first reason for this being fruit productivity. Until 10 years of age, fruit yield per unit area under the greenhouse-grown trellis-trained trees exceeded that of the modified-open-center-trained trees per unit area (Fig. 5). Under open field conditions, previous reports also showed superior productivity of trellis-trained trees when compared with modified-open-center-trained trees. For example, Ono and Kudo (1983) showed that fruit yield per unit area and uniformity of fruit quality under trellis-trained trees (300 trees per 1,000 m²) exceeded those of modified-open-center-trained trees (82–300 trees per 1,000 m²). Morinaga et al. (1982) showed similar results in trellis-trained trees (125–165 trees per 1,000 m²) against modified-open-center-trained trees (36 trees per 1,000 m²). These trends in fruit yield were explained by LAI related to planting density.
The second reason is canopy light distribution. In open field, Ono et al. (1987) showed that canopy light distribution of modified-open-center-trained trees was maintained at a good level when the canopy cover was under 60%. Several previous studies showed that low $K$ related to good canopy light distribution and high plant productivity (Higashide, 2018; Higashide and Heuvelink, 2009; Kubota et al., 1994; Monsi and Saeki, 1953). In this study, at 5 years of age, trellis-trained trees spread branches horizontally, meaning they showed high canopy cover at 78%–88% (Table 3) and high extinction coefficient $K$ at 1.89–6.35 (Table 3). Furthermore, 15-year-old trellis-trained trees showed lower $K$, at 0.49–0.51, with a low canopy cover of 59% (Table 3) when compared with modified-open-center-trained trees (Table 1). Data from this study showed that the canopy light distribution of 15-year-old trellis-trained trees must be superior compared with 5-year-old of those and modified-open-center-trained trees (Fig. 7c), with supporting previous observations. Additionally, Ono et al. (1980) showed that the utilization of solar radiation and photosynthesis rates were greater in the trellis-trained trees than modified-open-center-trained trees. This result also supports the good canopy light distribution of trellis-trained trees.

The third reason is capacity for increasing LAI. This is explained by the goodness of canopy light distribution. Low $K$ condition—large amount of radiation to the near bottom of canopy—is advantageous for sprouting new bud and increment of LAI. In open field, Ono (1982) showed the threshold level of relative light intensity for active vegetative growth as 10%–14%. In this study, 15-year-old trellis-trained trees showed large amount of radiation to the bottom of canopy as 12%–16% (percentage of $\overline{1}FPPFD$), whereas modified-open-center-trained trees showed small amount of that as 1%–8% (Fig. 8a). Therefore, 15-year-old trellis-trained trees had high capacity for increasing LAI as 4.0 m$^2$ m$^{-2}$ (Fig. 7b), which was supported by low $K$ condition with distributing large amount of radiation to the near bottom of canopy.

The fourth reason is labor cost. In this study, 15-year-old trellis-trained trees showed wide free alley width (Table 3), whereas modified-open-center-trained trees showed narrow free alley width (Table 1). The wide free alley width helps to save on labor costs for harvesting, transportation, and pesticide spraying.

4.3 Optimized planting and canopy dimensions

In the open field, early-flowering satsuma trees showed optimum LAI that maximized yields at 6.8 m$^2$ m$^{-2}$ when tree height was over 3 m with a closed canopy (Tachibana and Nakai, 1989; Tachibana, 1998). Similarly, in the heated greenhouse, the optimum LAI was reported at 5.7–5.9 m$^2$ m$^{-2}$ with near closed canopy (Tachibana and Yahata, 2007). However, in the greenhouse, to achieve both high fruit productivity and low-labor cost, optimizing planting and canopy dimensions must be an important criterion in the experimental process.

When comparing the spacing of trellis-trained trees, the present study results showed that both the 1.6 m×1.0 m and 2.2 m×1.0 m had high fruit yields per year, averaged until 10 years of age (Fig. 5). The 1.6 m×1.0 m had only narrow free alley width similar to modified-open-center-trained trees (Table 1 and 3), with planting tree numbers per unit area of 1.6 m×1.0 m 43% larger than that of 2.2 m×1.0 m (Table 3). Therefore, based on these costs for planting seedlings and the labor involved with fruit production, the 2.2 m×1.0 m was optimum. However, even when planting was 2.2 m×1.0 m, low LAI with large tree volumes or narrow free alley widths—such as the 5-year-old trees or modified-open-center-trained trees—would show worse canopy light distribution, represented by high $K$ (Table 3). Additionally, for such high $K$ situations, shading by woody elements must be marginal (Fig. 9). Hence, to decrease the negative effect of woody elements on fruit productivity, the compactness of a tree and increment of LAI is important for high productivity in trellis-trained trees.

Recently, studies on apples have revealed that the cultivation system has advantages for management and mechanization that enable narrow and planar canopies to be maintained under 1.0 m width with 2.7 m tree height was developed (Dorigoni and Micheli, 2015). In the present study, the canopy width of trained trees was set to 1.3–1.5 m. If more narrow and planar canopies were established for greenhouse-grown satsumas, optimum planting and canopy dimensions might be discovered and consequently used to update cultivation techniques.

4.4 Subjects for future study and short conclusion

In this study, the factors of LAI, extinction index $\Omega$, and clumping index $K$ were focused on as indices to characterize canopy structure. Here, to understand the availability of the indices in the greenhouse-grown satsumas, a more detailed discussion is needed. The first discussion point is the fluctuation of the $K$ value. Different to modeling studies assuming $K = 0.5$ (Green et al., 2003; Annandale et al., 2004), the present study directly measured the light absorption and LAI to estimate $K$. A relationship between $K$ and LAI was fitted to nonlinear functions (Fig. 8b), which is similar to several previous studies (Binkley et al., 2011; Brown and Parker, 1994; Sampson and Smith, 1993). Binkley et al. (2011) divided the patterns of light absorption in relation to leaf area into three patterns. According to these divisions, present study results (Fig. 8) were classified into the respective patterns instead of based on Beer’s Law. However, even when measurement error by a woody elements exists, in this study, empirical $K$ was at a good index. This could be because the index represented vertical canopy light distribution directly. Thus, a difference of $K$ between 15-year-old trellis-trained trees (average 0.5, Table 3) and modified-open-center-trained trees (average 1.6, Table 1) was considerable.

The second point is the clumping index. Generally, most natural forest and shrub canopies with high LAI values over 4.0 m$^2$ m$^{-2}$ were assumed to be clumped ($\Omega < 1$; Bréda, 2003; Chen et al., 2012). However, results for the greenhouse-grown satsumas differed to this; trellis-trained trees had low clumping indices ($\Omega < 1$), whereas modified-open-center-trained trees, which based on natural tree form, showed high clumping indices ($\Omega > 1$). To sufficiently understand and describe the canopy structure for high-yield, further examination for analyzing relationship among $\Omega$ and light distribution factors, such as $K$ and/or other indices—i.e., leaf inclination angle (Ryu et al., 2010)—must be essential.
In conclusion, LAI was the optimum index for determining fruit yield in greenhouse-grown satsumas. Though empirical K included some measurement error caused by woody elements, K was a good index to represent vertical canopy light distribution directly. From fruit productivity, canopy light distribution, and labor-cost, trellis-training method was superior to modified-open-center-training method.

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