agronomy

MDPI

Article

High-Density Espalier Trained Mangoes Make Better Use of Light

Kare P. Mahmud [1,2,*], Paula T. Ibell [2], Carole L. Wright [2], Dave Monks [1] and Ian Bally [2]

[1] New South Wales Department of Primary Industries, 1998 Silver City Hwy, Dareton, NSW 2717, Australia; dave.monks@dpi.nsw.gov.au

[2] Department of Agriculture and Fisheries, 28 Peters Street, Mareeba, QLD 4880, Australia; paula.ibell@griffith.edu.au (P.T.I.); carole.wright@daf.qld.gov.au (C.L.W.); ian.bally@daf.qld.gov.au (I.B.)

* Correspondence: kare.mahmud@dpie.nsw.gov.au; Tel.: +61-426660659

Abstract: Mango productivity and fruit quality in Australia can be improved through transforming low-density plantings to high-density plantings and intensive training systems. Several planting density and training systems were established in Australia to investigate optimizing light interception and distribution, yield and fruit quality, and to reduce tree vigor and biennial bearing through the manipulation of canopy architecture. In this research, we studied light relations and yield in conventional low-density commercial orchards of different ages and investigated light relations and yield of 'National Mango Breeding Program NMBP1243', 'Keitt' and 'Calypso' grafted to 'Kensington Pride (KP)' rootstock in a replicated experiment. Trees were trained to five planting systems: high-density espalier and conventional, medium-density single leader and conventional, and low-density conventional. Our study in commercial orchards showed that maximum yield was ~16,000 kg/ha when light interception reached ~49% and declined at higher levels of light interception. In the high-density intensive training systems, we found that light interception increased with canopy volume, with high-density espalier training systems intercepting more available light compared to medium-density training systems and low-density conventional trees. Yield/ha increased to ~50,000 kg/ha in espalier training systems when light interception was ~40%. Light interception, canopy volume and yield/ha varied between varieties.

Keywords: canopy volume; light interception; *Mangifera indica* L.; tree intensification; trellis training; variety; yield

Citation: Mahmud, K.P.; Ibell, P.T.; Wright, C.L.; Monks, D.; Bally, I. High-Density Espalier Trained Mangoes Make Better Use of Light. *Agronomy* **2023**, *13*, 2557. https://doi.org/10.3390/agronomy13102557

Academic Editor: Vasileios Ziogas

Received: 5 September 2023
Revised: 28 September 2023
Accepted: 28 September 2023
Published: 4 October 2023

1. Introduction

The adoption of high-density planting systems in mango (*Mangifera indica* L.) production is becoming increasingly popular in Australia due to its potential for earlier economic returns, sustained high yields of high-quality fruit, and reduced labor costs. However, the substantial establishment costs pose challenges to growers, requiring careful financial planning and risk assessment based on an understanding of how these new production systems differ from conventional systems. In the long run, those stated benefits of high-density planting systems are expected to outweigh the increased investment, making them a promising adaptation for the future of mango production.

The amount of light captured by interception, and how it is distributed within, a canopy drives photosynthetic energy for tree growth, flowering, fruit set, quality and colour development [1–3]. Interception and distribution are influenced by genetics, planting density, tree architecture and agronomic practices [4–7]. By planting trees at higher density, earlier cropping and higher yields have been achieved in some orchard crops because those additional trees/ha intercept more light/ha in the establishment years, before canopy closure is achieved, and can lead to a faster return on investment [8]. The amount of light intercepted/ha increases curvilinearly with increasing tree densities through increased canopy volume, a superior leaf area index (LAI) and a more even light distribution within the canopy [5,9–11]. A linear relationship exists between total light interception and biomass production and is a key driver of yield [12–14], with studies in some crops, including apple (*Malus* × *domestica*), showing that manipulation of tree architecture [15,16], with tree training and the removal of branches, increased yield compared with control trees. The relationship tends to break down at relatively high light interception values: in tree crops, maximum yield if often found at light interception between 60–80% of sunlight [17,18].

Mango is an evergreen tree crop grown commercially in over 100 countries in tropical and subtropical climatic regions [19]. It is the fifth most popular fruit worldwide [17]. Mango crops are terminal bearers and have been cultivated for at least 1500 years [18]. In Australia and in many other countries, mango is a relatively underdeveloped fruit tree crop and the orchard systems have undergone only slight changes over the past 50 years, integrating different varieties and mechanical pruning [19]. Most commercial orchards are planted conventionally at low densities (100–200 trees/ha) in anticipation of trees growing vigorously, producing large specimens at maturity. Kensington Pride (KP) is the most popular mango variety grown in Australia, grown throughout Australia's subtropical and tropical regions. Because of KP's vigour, trees are traditionally planted at relatively wide spacing 10 × 10 m or 12 × 12 m (giving 100 and 70 trees/ha, respectively). Over time, these trees fill their allocated space and reach heights of 6 m or more. In recent years, mango plant spacings have reduced to an average plant spacing of 6 × 9 m (185 trees/ha). Previous attempts to increase planting density in KP failed due to overcrowding and tree vigour requiring excessive pruning that caused yield reduction [20]. Growers using these closer spacings have committed to annual pruning to maintain a smaller canopy size. Generally, canopies are grown to touch in the row to maximise light interception and heights are kept to ~5 m for ease of spraying and picking. However, there are few reports available on the relationship between productivity and light interception in mango orchards.

The estimation of productivity and light interception in mango orchards over time is difficult as some cultivars have biennial and irregular bearing patterns and there can be strong rootstock effects [21]. However, KP grown in northern Australia had nearly linear increases in fruit production from the first year of production through to 10 years [22]. Singh et al. [23] reported that productivity of conventionally planted mango orchards started to decline when trees reached 23–26 years old and had poor total orchard light interception.

Tree training methods, such as espalier systems, can be employed to manipulate leaf distribution and light penetration within a canopy [24]. These techniques can be tailored to manage the canopy's architecture and light interception, driving more efficient use of the available light resources. This manipulation of tree shoot architecture changes light interception and distribution within canopy change in an attempt to optimize radiation use efficiency [24].

The mango industry's transition from conventional, large-tree orchards to smallertree orchards has potential to improve profits for mango growers. However, there is little understanding of how the total light interception of mango orchards and light distribution are related to mango training systems and productivity. The objectives of this research were to document the relationships between light interception, canopy size, and yield in young mango trees using higher-density planting systems in combination with three different varieties. Additionally, we conducted a study in conventional orchards to compare light relations with alternative planting systems. Our study aims to provide valuable information for farmers, agronomists, and scientists, which will be useful for optimizing canopy management and light interception to maximize fruit productivity in the industry.

2. Materials and Methods

2.1. Light Interception in Low-Density, Conventionally Trained Trees in Commercial Mango Orchards

We conducted a survey to establish baseline light relationships in commercial KP mango orchards using conventional planting system in the Mareeba/Dimbula district of Queensland with soils varying from granitic sands to volcanic light clays. All orchards in this study were irrigated using channel water from lake Tinaroo. We measured total light interception, canopy volume and tree yield using nine orchard blocks of different ages, (2, 4, 8, 9, 10, 13, 26, 28 and 31 years old) producing data in developing orchards with varying canopy size in the low-density plantings. Each block was planted at conventional low-density, with 185, 185, 185, 156, 185, 173, 128, 139 and 196 trees/ha respectively, and conventionally trained. Within each orchard block, five trees were selected to represent an individual experimental unit, with the central three used as datum trees. In July 2015, the transmission of total photosynthetic active radiation (PAR) under the canopy of each tree was measured using an AccuPAR linear ceptometer (model LP-80, Decagon Devices Inc., Pullman, WA, USA) for calculation of the proportion of light intercepted by the canopy. Canopy dimensions (tree height, width, depth, and skirt) were measured to calculate tree volume and yield/m^3 canopy volume. Tree yield was estimated for all datum trees in each orchard prior to harvest by counting the number of fruit/tree and multiplying by the average fruit weight of a sub-sample of 10 fruit/tree in 2015. Yield (kg/ha) was calculated using the average of the three tree yields multiplied by trees/ha.

2.2. Light Relationships in High-Density, Intensive Orchards with Alternative Tree Training Systems

We studied light relationships in intensive mango planting and training orchard systems to investigate how light relations were affected by planting density and canopy training. The planting systems experiment was designed as a split-split plot with density as the main plot, training system as sub-plot and variety as lower sub-sub-plot. The experimental site was located on the Queensland Department of Agriculture's Walkamin Research Facility in the Walkamin district of Queensland, Australia (Latitude: 17.13 °S Longitude: 145.43 °E, Elevation: 594 m). The site has a dry topical climate with a mean annual maximum 24.7 °C and minimum 17.1 °C temperature, 1026 mm mean annual rainfall and a mean of 7.8 h of sunshine per day [25]. Trees were planted in December 2014 with KP rootstock. Three varieties, National Mango Breeding Program NMBP1243, Keitt and Calypso were planted at 3 densities. Low-density 8 m × 6 m = 208 trees/ha, medium-density 6 m × 4 m = 417 trees/ha, high-density 4 m × 2 m = 1250 trees/ha. Within the medium-density treatment, there were two training systems: conventional and single leader. Within the high-density treatment, there were two training systems: espalier and conventional. Each planting system was replicated six times. Each sub-sub-plot comprised 3 datum trees, except the high-density espalier sub-sub-plots comprised 4 datum trees. Rows within the experiment run north to south. In the low-density treatment, trees were grown naturally with no training. In the medium-density treatment, trees were trained as either conventional or as single leader. In the high-density treatments, trees were trained as either conventional or as espalier on trellis. The main scaffold limbs in the single leader and espalier training systems were trained (bent) horizontally every 60 cm. Trees in each planting systems were pruned annually just after harvest.

2.3. Light Interception, Tree Volume and Yield Data Collection in Intensive Planting Systems

Photosynthetic photon flux (PPF) was measured using 15 Apogee SQ -100 PAR point sensors (Apogee Instruments, Logan, UT, USA) mounted atop a 427 cm long aluminium arm with spacing of 30 cm. The aluminium arm was mounted to a modified trolley and the sensors were connected to a CR1000X Series (Campbell Scientific, Garbutt, Australia) data logger. A PC200W (Data Logger Starter Software, Version 4.5, Campbell Scientific, Inc., Logan, UT, USA) data logger was used for data collection. Light measurements were recorded for all 288 datum trees for intensive mango planting systems treatments. Light interception was measured on cloud-free days, five times throughout the day: early morning, mid-morning, solar noon, mid-afternoon and late afternoon. The value was generated by averaging these readings. The time for each of these sampling events were calculated as 1.5 h and 3 h before and after solar noon on the day the measures were taken. With rows running due North/South, data collected at the corresponding time from the morning or afternoon was substituted if data was not able to be recorded at the equal but opposite time of the day. Above canopy light data was collected in each density at the end of every two rows under the condition of full sun. We calculated light interception for each sub-sub-plot as the proportion of incident above canopy PPF reaching the orchard floor for each measurement, using the average of all the measurements within the sub-sub-plot. The light interception and canopy volume/ha were measured in the planting systems experiment in 2015, 2016, 2017 and 2018 when the trees were 2, 3, 4 and 5 years old.

We measured tree canopy volume for each datum tree and the mean canopy volume/ha was calculated to give one corresponding value per sub-sub-plot. Canopy volume for conventional trees was calculated using length × width × canopy height. Canopy volume in the medium-density single leader trees was calculated as the volume of a cylinder ($\pi r^2 h$) (where r is the radius and h is the canopy height) multiplied by the percentage of canopy on each 50 cm interval. Canopy volume in the high-density espalier trees was calculated as the volume of a trapezoidal prism LH(A+B)/2 where: L is the depth of the canopy; H is the height of the total canopy minus the gaps in between the scaffolds of canopy; A+B is the length of the canopy along the row at the top of the canopy plus the length of canopy along the row of the bottom of the canopy.

We harvested the datum trees and weighed fruit between late December and early February in 2016, 2017 and 2018. No yield data was recorded in 2015 (2 year old trees). Every individual fruit in each datum tree was weighed in 2016 and 2018 whereas a random selection of 25 fruit/tree were weighed in 2017 to estimate average fruit weight/tree.

2.4. Statistical Methods

Analysis of variance (ANOVA) was used to analyse the mean light interception in both experiments for each individual measurement event. All significance testing was performed at the 0.05 level and where a significant effect was found, the pairwise 95% least significant difference (lsd) was used to make comparisons. Linear and non-linear models were used to investigate relationships between variables measured within the light interception experiments. A log10 transformation was applied when needed to satisfy the assumption of homogeneity of variance and normality underlying the ANOVA performed on data from the planting systems experiment.

3. Results

3.1. Relationship between Light Interception, Canopy Volume and Yield in Low-Density, Conventionally Trained Trees in Commercial KP Orchards

A significant relationship was found between canopy volume (m^3/ha) and the proportion of light intercepted for conventionally trained commercial KP. A broken stick model (adj R^2 = 89.4%; $p < 0.001$) estimated the maximum proportion of intercepted by the tree canopy light (canopy closure) for the conventional planting systems at ~67% (se = 2.1) when the canopy volume reached ~15,200 m^3/ha (se = 403.2) (Figure 1). As canopy volume increased beyond this size, the light interception remained stable. Additionally, we investigated the relationship between light interception and orchard yield (kg/ha) in 2015. A B-spline basis function explained 64.9% of the variation and the upper asymptote was ~16,000 kg/ha. The yield/ha declined once light interception reached above ~55% (Figure 2), corresponding to trees $\geq$ 26 years old.

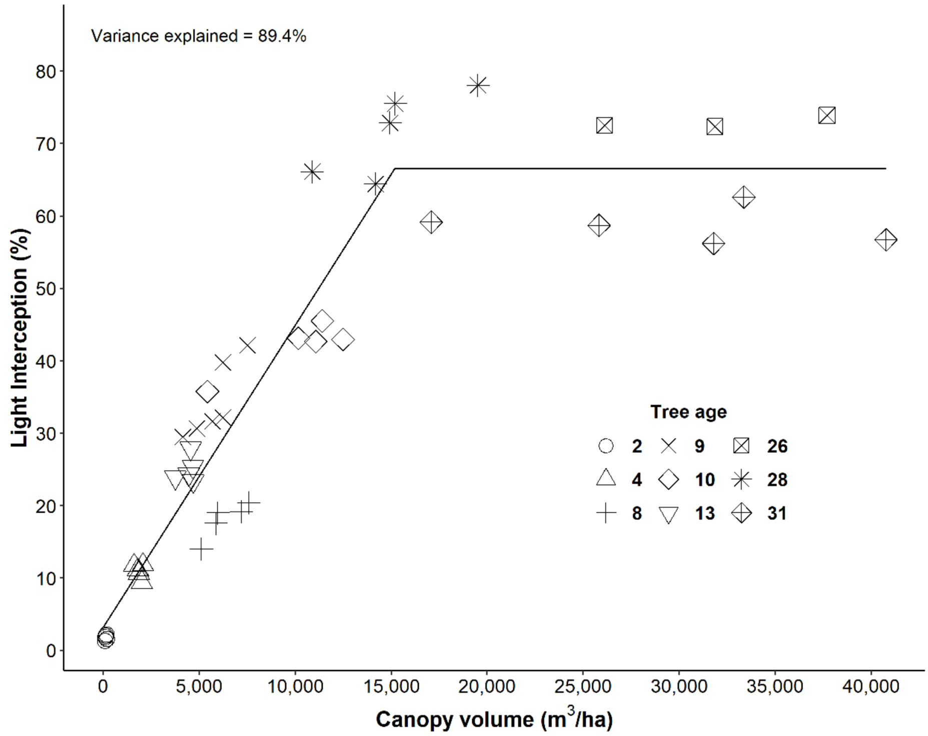

Figure 1. The relationship between canopy volume (m^3/ha) and the percentage of sunlight intercepted by the tree canopy for conventionally trained Kensington Pride mango trees of different ages, grown at different sites in the Mareeba/Dimbulah region of Queensland. This model is using broken stick model functions.

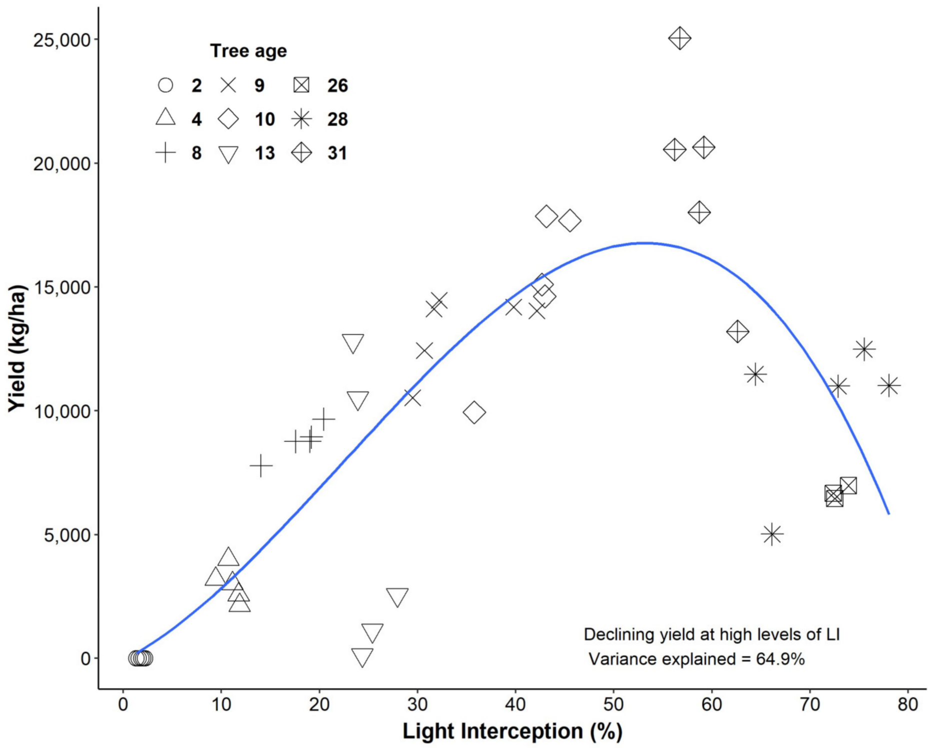

Figure 2. The relationship between yield/ha and the percentage of sunlight intercepted by the tree canopy for conventionally trained Kensington Pride mango trees of different ages, grown at different sites in the Mareeba/Dimbulah region of Queensland. The model is using B-spline basis functions.

3.2. *The Alternative Intensive Planting Systems Experiment*

3.2.1. Canopy Volume Changes over Time (m^3/ha)

A $\log_{10}$ transformation was applied to canopy volume measurements at all ages analysed. The canopy volume (m^3/ha) in the alternative systems was significantly affected by training systems within density ($p \leq 0.046$) in each of the four years (Figure 3). Mean canopy volume/ha tended to increase over time with increasing orchard age in all planting densities. The highest mean canopy volumes/ha (3899 m^3/ha) were measured in the high-density espalier plantings at 4 years of age. In both the 3rd and 4th years, high-density espalier trees had a significantly higher mean canopy volume compared to any other planting system in the same year. Single leader trees in medium-density had lower mean canopy volume/ha in the first two years of growth. However, by age 4 those medium-density single leader trees had significantly larger canopy volume compared to the trees at low-density, and, for Keitt and NMBP1243, had significantly larger canopy volume than medium-density conventional trees by age.

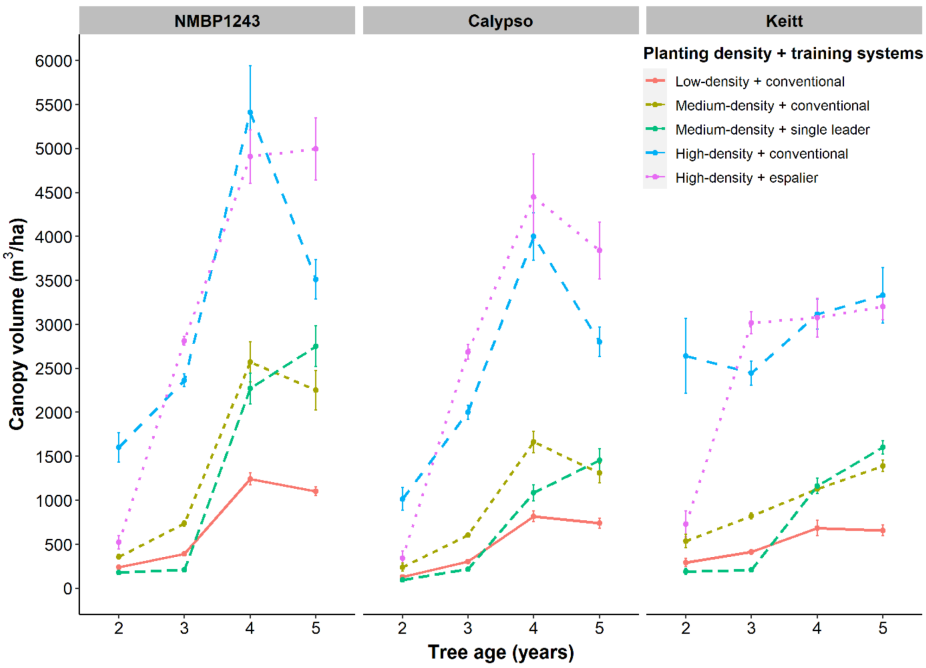

Figure 3. Mean canopy volume (m^3/ha) of three mango varieties over time for five planting systems treatments grown at Walkamin, Queensland. Bars indicates the standard error (n = 6).

Additionally, we found a significant effect between varieties on tree size development over time ($p < 0.001$) (Figure 3). In pairwise comparisons of the variety means at age 2 and 3 and 4, we found that Calypso had the smallest mean canopy volume/ha and Keitt had the largest.

The interaction of density, training system and variety was significant in year three ($p < 0.001$) and marginally significant ($p = 0.052$) in year 4. Keitt trees had larger canopies than Calypso and NMBP1243 within high-density training systems when trees were 2 and 3 years old, but NMBP1243 had larger mean canopy volume in each planting system compared to the other two varieties in year 4. At 4 and 5 years old, Calypso and Keitt had similar canopy size at low and medium density.

3.2.2. Light Interception (%)

A $\log_{10}$ transformation was required for the analysis of light interception when trees were 2 years old. For the different planting systems, light interception was mainly affected by density and variety ($p < 0.001$) over the three years. The mean light interception increased significantly as planting density increased (Figure 4). Within varieties, we found that Calypso had a significantly lower mean light interception while Keitt had a significantly higher mean (Figure 5). The interaction between training system within density had significant effect on light interception in three-year-old trees ($p < 0.001$) where high-density conventional trees intercepted more light compared to other density training systems (Figure 4).

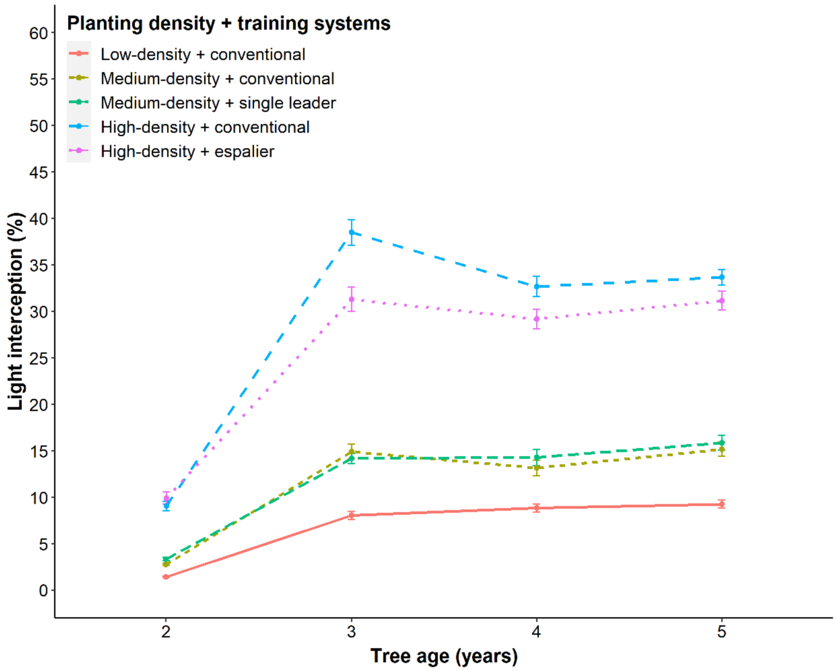

Figure 4. Mean light interception (%) over time of three mango varieties combined in five combinations of planting systems grown at Walkamin, Queensland (n = 18). Bars indicates the standard error.

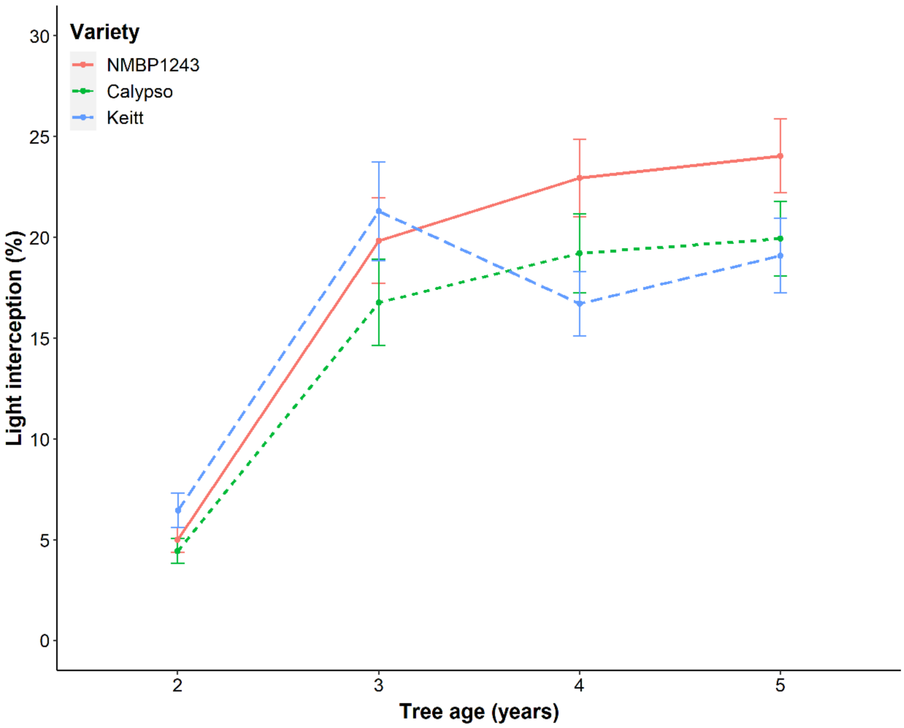

Figure 5. Mean light interception (%) over time of three mango varieties for combined planting systems grown at Walkamin, Queensland. Bars indicates the standard error.

We found that all main effects and interactions were significant when the orchard reached four years old (Table 1). Focusing on the highest order interaction, pairwise comparisons at high-density found no significant difference between the conventional and single leader trees for Calypso and Keitt, but conventional NMBP1243 had a higher mean light interception than single leader NMBP1243. At medium-density, there was no significant difference between conventional and single leader trees for the three varieties. At low-density, conventional NMBP1243 and Calypso trees had a significantly lower mean light interception than all other treatments. The low-density conventional Keitt trees were not significantly different to the medium-density conventional Keitt trees. Across all treatments, NMBP1243 had the highest mean light interception. Keitt had a significantly lower mean light interception than NMBP1243 for all treatments. Calypso was not significantly different to NMBP1243 for high-density espalier and low-density conventional. For all other treatments, Calypso had a significantly lower mean than NMBP1243 (Figure 5).

Table 1. Mean light interception (%) in three varieties of four-year-old mango trees grown in different planting systems. * Means followed by the same letter within and across a column are not significantly different using least significant difference test ($p = 0.05$).

Density	Training Systems	NMBP1243	Calypso	Keitt
Low	conventional	10.12 bcd *	8.60 ab	7.83 a
Medium	conventional	16.77 e	12.56 d	10.10 abc
	single leader	18.78 e	12.05 cd	12.00 cd
High	conventional	37.84 i	32.34 h	27.82 fg
	espalier	31.27 h	30.48 gh	25.82 f

3.2.3. Yield/ha

A $\log_{10}$ transformation was required for the analysis of yield when trees were 4 and 5 years old. Yield was significantly affected by the interaction of planting density and variety (Figure 6) when trees were 3 and 5 years old ($p < 0.001$). At 3 years old, there was no significant effect of density on mean yield for variety NMBP1243. At both 3 and 5 years of age, the Keitt and Calypso high-density trees had significantly higher mean yields than the low- and medium-densities. Keitt consistently had the highest mean yield at each planting density, but at 3 years of age yield was not significantly higher than NMBP1243 or Calypso in the low planting density. The three-way interaction of planting systems and variety was significant for the mean yield in year four (Figure 6). At this age, the low-density conventional mean yield was significantly lower than all other planting systems for each of the three varieties.

At 4 and 5 years of age, the highest mean yield for each of the three varieties was the high-density espalier trees. At age 4, the mean yield for Keitt high-density espalier was significantly higher than all other planting systems, but there was no significant difference between high-density conventional and high-density espalier for NMBP1243 or Calypso. There was no significant difference between the medium-density training systems for each of the three varieties at any age. Keitt had significantly higher mean yields than NMBP1243 for all planting systems at age 4, but was only significantly higher than Calypso when grown as medium-density single leader trees.

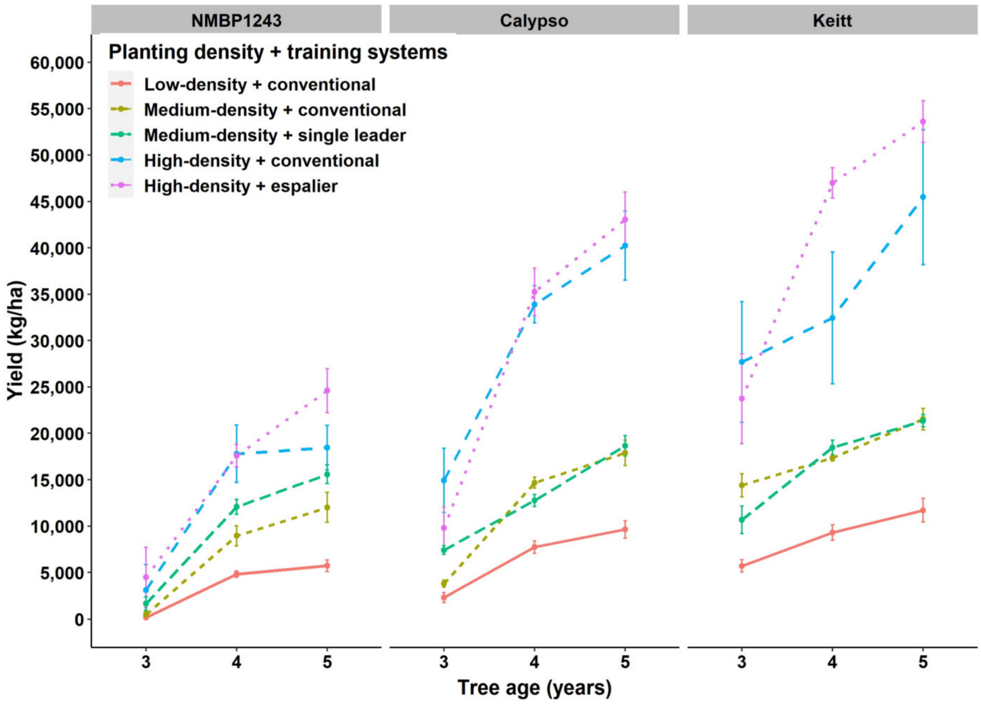

Figure 6. Three-way interactions on yield (kg/ha) over time. Yield data only recorded when trees are three, four and five years old. Trees were grown at Walkamin, Queensland. Bars indicates the standard error.

3.2.4. Relationship between Canopy Volume m^3/ha and Light Interception

A line-plus-exponential model was fitted to the relationship between canopy volume (m^3/ha) and light interception across data from all years and explained 92% of the variance ($p < 0.001$) (Figure 7A). The high-density planting systems had significantly higher canopy volume m^3/ha and light interception compared to medium-density and low-density. When training systems are introduced into the model, a significant relationship is found ($p < 0.001$). The linear-divided-by-linear model (Figure 7B) with training system (conventional, medium-density single leader, high-density espalier) has an adjusted R^2 = 94%.

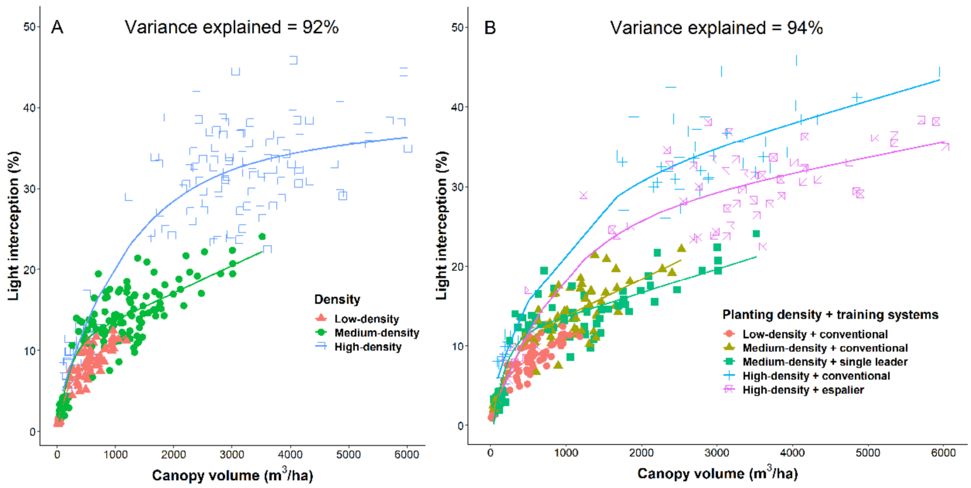

Figure 7. The relationship between light interception (%) and canopy volume (m^3/ha) for mango planting system experiment from 2015 to 2018 for trees grown at Walkamin, Queensland. (**A**) Model excluding training systems. (**B**) Includes training systems in each density.

3.2.5. Effect of Canopy Volume m^3/ha and Light Interception on Yield

We used two non-linear regression models to represent the relationship of yield/ha with canopy volume and light interception across data from years 3, 4 and 5. The models required separate lines for the three varieties and explained 69% (Figure 8) and 58% (Figure 9) of the variance respectively ($p < 0.001$). Yield increased with increased canopy volume in all varieties. Keitt had the highest yield overall and NMBP1243 had the lowest.

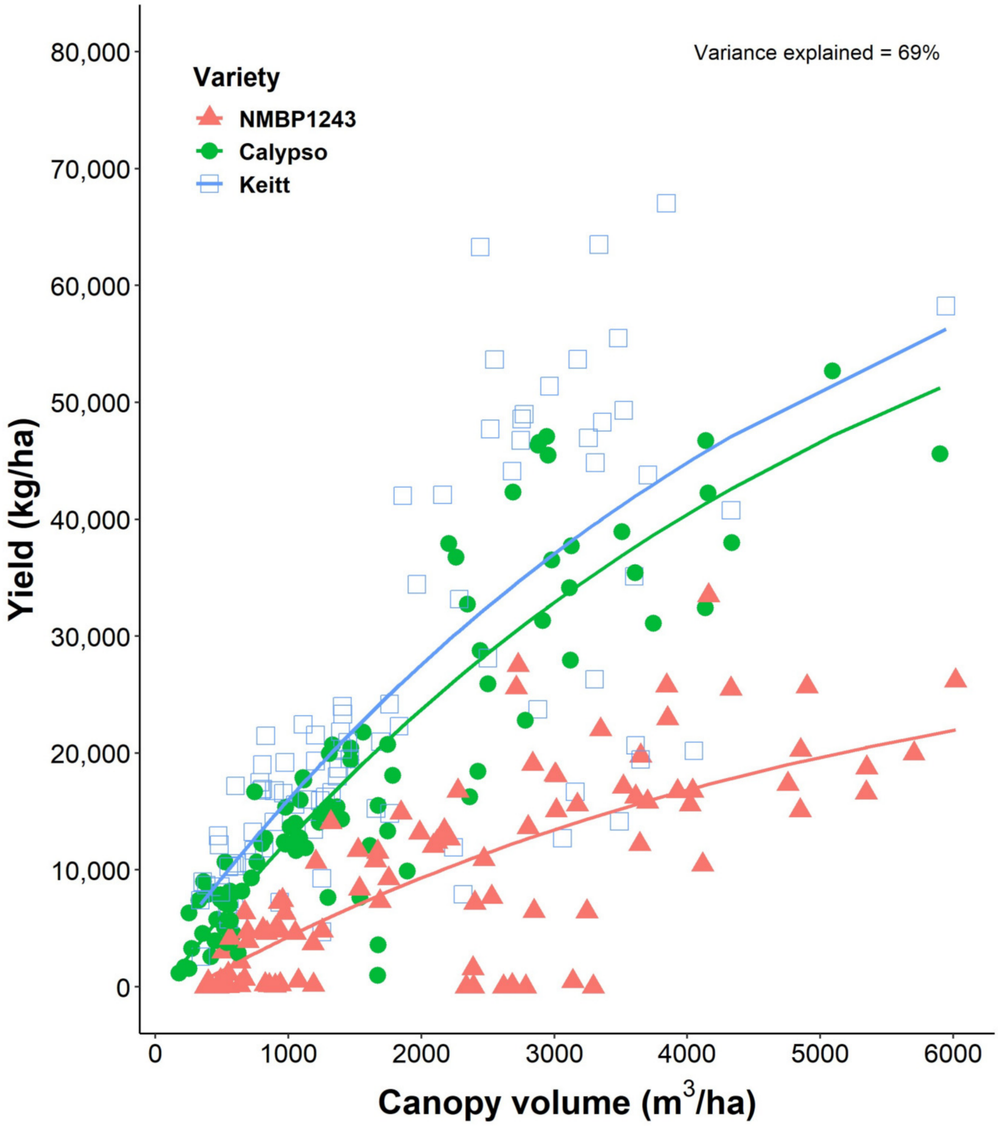

Figure 8. Relationships between yield and canopy volume for the NMBP1243, Calypso and Keitt mango varieties grown at Walkamin, Queensland. The fitted curves are an exponential model with adj R^2 = 69% ($p < 0.001$).

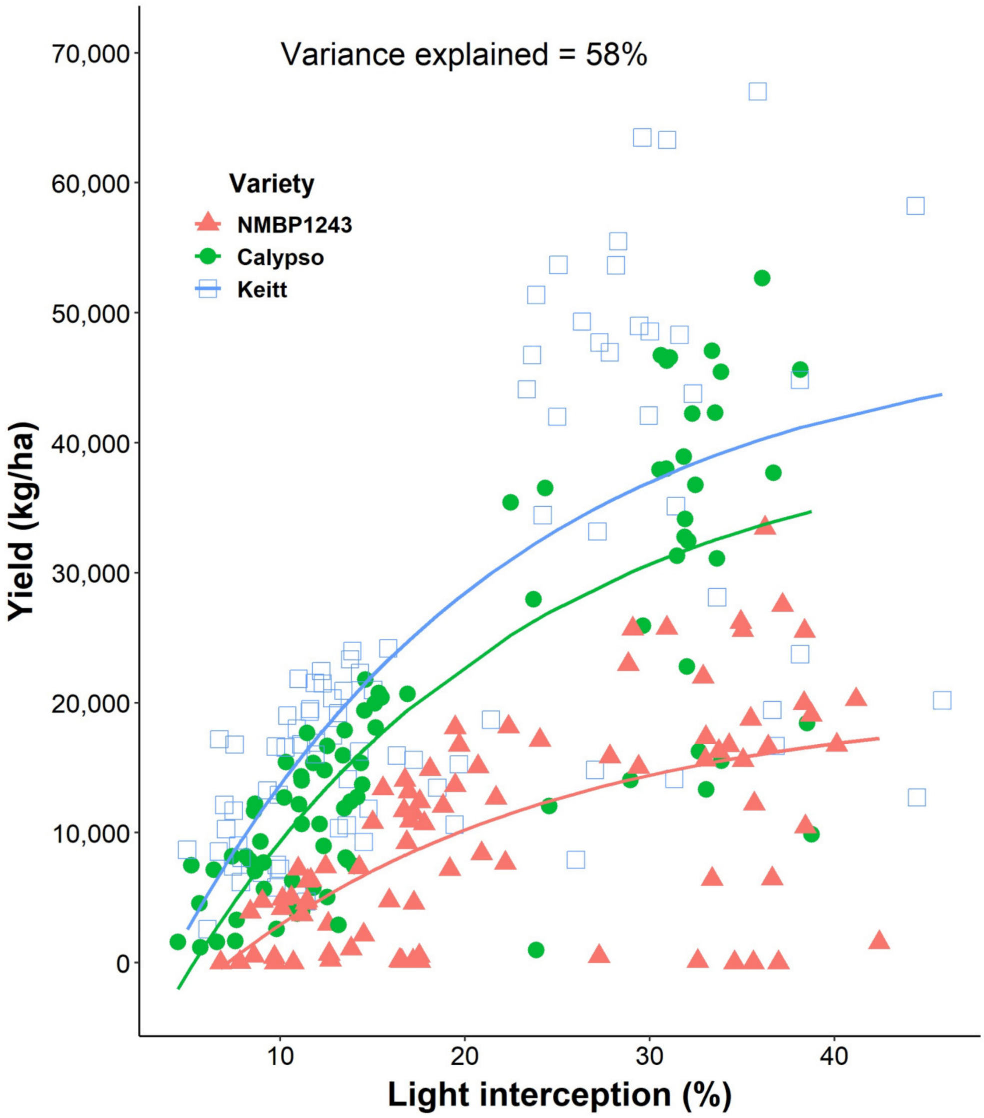

Figure 9. Relationships between yield and light intercepted by the canopy for the mango varieties NMBP1243, Calypso and Keitt grown at Walkamin, Queensland. The fitted curves are an exponential model with adj R^2 = 58% ($p < 0.001$).

4. Discussion

Mango is a high value fruit and growers want to maximise their returns by increasing the amount of light intercepted, and the rate at which that energy is converted to salable fruit, so are investigating planting higher-density planting systems. The authors have observed growers adopting annual pruning methods. Case studies wherein orchards planted under high-density or ultra-high-density but without adopting the mandatory techniques, resulting in poor yield and more pest and disease incidences are discussed [26]. Therefore, consistent tree training or pruning is necessary. In addition, increased light interception results in increased dry matter accumulation/ha [11], but not necessarily fruit if this energy is used for vegetative growth. These relationships highlight important trends with canopy volume, management and yield where there is competition between vegetative growth and fruiting. Studies on apple showed that the initial establishment costs of trellis and branch training and pruning of espalier and non-trellis single leader systems are high, with the risk of the extra pruning stimulating unwanted vegetative growth in the place of reproductive growth [27]. This study provides some physiologically-based measurement of canopy response to training method and planting density, in the hope that sensible guidelines can be developed to assist growers to manage blocks planted at high-density profitably.

In our observations of traditional low-density mango orchards, the trees reached canopy volumes of up to 15,200 m^3/ha with light interception of 67% between their 13th and 26th year (Figure 1). This maximum observed level of light interception is similar to those commonly measured in apple orchards (~60–70%) [6]. Our yield observations in traditional mango orchards showed yields reached a mean maximum of 16,000 kg/ha when the canopy intercepted 55% of incident light. Yields declined at higher light interception (Figure 2), similar to that seen in apple orchards, where yields declined after 60% light interception [17,27]. Beyond that 55% light threshold, those traditional low-density mango trees increased light interception up to 67%, but the energy demand by the fruit reduced and resources can be partitioned and shifted to vegetative growth [28]. Mango trees may have very low photosynthetic rates per unit of leaf area, especially in the inner- and lower-canopy area because they may have very low light distribution within their canopies. It is worthwhile to do further study to understand this better.

As 4-year-old trees, conventional planting Kensington Pride (180 trees/ha) had grown its canopy to ~1900 m^3/ha, or 10.55 m^3/tree (Figure 2). At the same age, NMBP1243, Calypso and Keitt, planted at 204 trees/ha, had grown their canopies to 1243, 816 and 683 m^3/ha, respectively, or 6.1, 4.0 and 3.3 m^3/tree, respectively (Figure 3). In the fifth and final year of our study, NMBP1243 mango trees, the fastest growing in our intensive planting systems experiment, planted at high-density had reached ~40% of the canopy volume achieved in mature, conventional KP orchards at canopy closure (6000 m^3/ha cf. 15,200 m^3/ha, Figures 3 and 9). These high-density NMBP1243 trees, planted at 1250 trees/ha, correspond to a similar amount intercepted as that shown in 8-, 9- and 10-year-old KP orchards planted at low-density (180 trees/ha). On a per-tree basis, those same KP trees grew at a rate of 3.7 m^3/tree/year, compared with 0.96 m^3/tree/year for NMBP1243, demonstrating KP's known status as a vigorous mango variety.

Our research has shown that higher density planting in mango increased the canopy volume/ha leading to an increase in light interception in the orchard compared to the conventional low- density conventional training systems in coming years, light interception will increase in the espalier and non-trellis single leader training systems once the tree structure is shaped and has reached their allotted space. The young trees in high density training systems reached ~55,000 kg/ha (Figure 6). In this research, yield was the result of a combination of genotype and their biennial bearing characteristics. Keitt had the highest yield compared to Calypso and NMBP1243, despite a smaller canopy volume (Figure 3) and lower light interception (Table 1 and Figure 5). The lower canopy volume in Keitt was not due to pruning or training. It is result of the natural growth habit and tree architecture of Keitt. The decrease in canopy volume of Calypso and NMBP1243 in high density (Figure 3) in year 5 was due to pruning and training of espalier and hedging of the conventional trees. In addition, no relationship between light interception and yield was found, showing the irregular nature of mature mango canopies to fruit [29,30]. The yield was greater in year 5 compared to year 4, which was opposite to the trend observed between canopy volume (Figure 3) and light interception (Figure 4). We observed a trend toward a further increase in light capture by the tree canopy using different canopy training systems. Training systems can change light distribution through the canopy and how it is intercepted across the orchard floor [11,24].

Therefore, we propose that high-density training systems lead to greater economicyield earlier in the life of the tree compared to conventional orchard systems [31]. This is tempered by the significant difference between varieties. Jackson and Palmer [5,10] suggested that by implementing different training methods we can increase tree height, and with appropriate pruning and training we can increase light use efficiency, due to taller thinner canopies and lower leaf density which positively influences internal canopy irradiance. The optimisation of light interception and canopy irradiance are considered as prerequisites for effective production and high fruit quality [32]. Our results show how light interception can be increased in young mango canopies by increasing planting density and by using alternative single leader training systems which leads the early yield gain per unit land area compared to low tree density. The espalier and single leader systems suggested that such training may increase trellis and training cost, but ease canopy management in longer term [31]. Mango growers can choose a suitable training system based on their personal preference.

5. Conclusions

Our research demonstrated that a relationship exists among canopy size, light interception and yield in conventional mango orchards. Conventional mango orchard planting configurations reach maximum production and light interception between 13–26 years after which yields do not increase further. Intensive orchards using high-density configurations and different canopy training systems provide techniques to increase canopy volume and light interception early in the orchard's life. Additionally, these changes may provide opportunity to increase production over the orchard area, as shown by the relationships that exist between canopy volume, light interception and yield. High density must be combined with modern training systems to reduce vigor and increase light interception and yield, while optimizing the distribution, fruit quality and cost of production. Consideration must also be given to the role variety selection can play in managing vigour to ease the ongoing cost of pruning.

Author Contributions: Conceptualization, I.B. and P.T.I.; methodology, K.P.M.; software, K.P.M.; validation, K.P.M., C.L.W. and P.T.I.; formal analysis, C.L.W.; investigation, K.P.M.; resources, I.B.; data curation, K.P.M.; writing—original draft preparation, K.P.M.; writing—review and editing, K.P.M., I.B., C.L.W., D.M. and P.T.I.; visualization, K.P.M.; supervision, I.B.; project administration, I.B.; funding acquisition, I.B. All authors have read and agreed to the published version of the manuscript.

Funding: This is a project of the Transforming Subtropical/Tropical Tree Crop Productivity in Horticulture Program (AI13004), funded by the Hort Frontiers strategic partnership initiative developed by Hort Innovation, with co-investment from Queensland's Department of Agriculture and Fisheries, Queensland Alliance for Agriculture and Food Innovation, The University of Queensland, NSW Department of Primary Industries, and contributions from the Australian Government.

Data Availability Statement: Data is unavailable due to privacy or ethical restrictions.

Acknowledgments: The authors wish to thank technical officer Zac Scobell for his outstanding contribution of field data collection. Special thanks to collaborating farmers in Mutchilba and Dimbulah, Far North Queensland for their ongoing support with sites for the light interception baseline studies. Bernie Dominiak reviewed an early version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tucker, D.P.H.; Wheaton, T.A.; Muraro, R. *Citrus Tree Pruning Principles and Practices*; University of Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences: Newberry, FL, USA, 1994.
2. Krajewski, A.; Pittaway, T. Manipulation of citrus flowering and fruiting by pruning. In Proceedings of the International Citrus Congresses, Orlando, FL, USA, 3–7 December 2000; pp. 3–7.
3. Singh, J.; Marboh, E.S.; Singh, P.; Poojan, S. Light interception under different training system and high density planting in fruit crops. *J. Pharmacogn. Phytochem.* **2020**, *9*, 611–616.
4. Thornley, J.H. *Mathematical Models in Plant Physiology*; Academic Press (Inc.), Ltd.: London, UK, 1976.
5. Jackson, J.; Palmer, J. A computer model study of light interception by orchards in relation to mechanised harvesting and management. *Sci. Hortic.* **1980**, *13*, 1–7. [CrossRef]
6. Jackson, J.E. Light interception and utilization by orchard systems. *Hortic. Rev.* **1980**, *2*, 208–267.
7. Da Silva, D.; Han, L.; Costes, E. Light interception efficiency of apple trees: A multiscale computational study based on MAppleT. *Ecol. Model.* **2014**, *290*, 45–53. [CrossRef]
8. Elkins, R.B.; Klonsky, K.; DeMoura, R.; DeJong, T.M. Economic evaluation of high density versus standard orchard configurations; case study using performance data for 'Golden Russet Bosc'pears. *Acta Hortic.* **2008**, *800*, 739–746. [CrossRef]
9. Palmer, J. *Canopy Manipulation for Optimum Utilization of Light*; Butterworths: London, UK, 1989.
10. Palmer, J.; Avery, D.; Wertheim, S. Effect of apple tree spacing and summer pruning on leaf area distribution and light interception. *Sci. Hortic.* **1992**, *52*, 303–312. [CrossRef]

11. Wünsche, J.N.; Lakso, A.N.; Robinson, T.L.; Lenz, F.; Denning, S.S. The bases of productivity in apple production systems: The role of light interception by different shoot types. *J. Am. Soc. Hortic. Sci.* **1996**, *121*, 886–893. [CrossRef]
12. Monteith, J. Light distribution and photosynthesis in field crops. *Ann. Bot.* **1965**, *29*, 17–37. [CrossRef]
13. Cannell, M.; Sheppard, L.; Milne, R. Light use efficiency and woody biomass production of poplar and willow. *For. Int. J. For. Res.* **1988**, *61*, 125–136. [CrossRef]
14. Rosati, A.; Dejong, T. Estimating photosynthetic radiation use efficiency using incident light and photosynthesis of individual leaves. *Ann. Bot.* **2003**, *91*, 869–877. [CrossRef]
15. Willaume, M.; Lauri, P.-É.; Sinoquet, H. Light interception in apple trees influenced by canopy architecture manipulation. *Trees* **2004**, *18*, 705–713. [CrossRef]
16. Lauri, P.-E.; Costes, E.; Regnard, J.-L.; Brun, L.; Simon, S.; Monney, P.; Sinoquet, H. Does knowledge on fruit tree architecture and its implications for orchard management improve horticultural sustainability? An overview of recent advances in the apple. In Proceedings of the I International Symposium on Horticulture in Europe, Wien, Austria, 17–20 February 2008; pp. 243–250.
17. Wünsche, J.N.; Lakso, A.N. The relationship between leaf area and light interception by spur and extension shoot leaves and apple orchard productivity. *HortScience* **2000**, *35*, 1202–1206. [CrossRef]
18. Castillo-Ruiz, F.J.; Castro-Garcia, S.; Blanco-Roldan, G.L.; Sola-Guirado, R.R.; Gil-Ribes, J.A. Olive crown porosity measurement based on radiation transmittance: An assessment of pruning effect. *Sensors* **2016**, *16*, 723. [CrossRef]
19. Bally, I.S.; Johnson, P.; Kulkarni, V. Mango production in Australia. In Proceedings of the VI International Symposium on Mango, Pattaya City, Thailand, 6–9 April 1999; pp. 59–68.
20. Menzel, C.M.; Le Lagadec, M. Can the productivity of mango orchards be increased by using high-density plantings? *Sci. Hortic.* **2017**, *219*, 222–263. [CrossRef]
21. Smith, M.W.; Hoult, M.D.; Bright, J.D. Rootstock affects yield, yield efficiency, and harvest rate of 'Kensington Pride' mango. *HortScience* **2003**, *38*, 273–276. [CrossRef]
22. Bally, I.; Harris, M.; Foster, S. Yield comparisons and cropping patterns of Kensington Pride mango selections. *Aust. J. Exp. Agric.* **2002**, *42*, 1009–1015. [CrossRef]
23. Singh, S.K.; Singh, S.; Sharma, R. Pruning alters fruit quality of mango cultivars (*Mangifera indica* L.) under high density planting. *J. Trop. Agric.* **2010**, *48*, 55–57.
24. Mahmud, K.; Ibell, P.; Wright, C.; Scobell, Z.; Bally, I.; Monks, D. The effect of different mango training systems on light transmission within the canopy. In Proceedings of the XXXI International Horticultural Congress (IHC2022): International Symposium on Innovative Perennial Crops Management, Angers, France, 14–20 August 2022; pp. 345–352.
25. Malcolm, D.T.; Heiner, I.J. *The Soils of Walkamin Research Station*; Resource Management, Department of Primary Industries: Brisbane, QLD, Australia, 1996; pp. 1–58.
26. Verheij, E.; Verwer, F. Light studies in a spacing trial with apple on a dwarfing and a semi-dwarfing rootstock. *Sci. Hortic.* **1973**, *1*, 25–42. [CrossRef]
27. Campbell, J.; Nicol, H.; Cullis, B. Effect of four different canopy shapes on apple yields. *Aust. J. Exp. Agric.* **1996**, *36*, 489–499. [CrossRef]
28. Wünsche, J.; Palmer, J. Effects of fruiting on seasonal leaf and whole-canopy carbon dioxide exchange of apple. In Proceedings of the VI International Symposium on Integrated Canopy, Rootstock, Environmental Physiology in Orchard Systems, Wenatchee, WA, USA, 17 July 1996; pp. 295–302.
29. Monselise, S.; Goldschmidt, E. Alternate bearing in fruit trees. *Hortic. Rev.* **1982**, *4*, 128–173.
30. Mukherjee, S. Origin of mango (*Mangifera indica*). *Econ. Bot.* **1972**, *26*, 260–264. [CrossRef]
31. Bennett, D.; Dickinson, G. *An Economic Case Study of Intensive Mango Systems*; Department of Agriculture and Fisheries Queensland: Brisbane, QLD, Australia, 2021; pp. 1–30.
32. Tustin, D.; Cashmore, W.; Bensley, R. The influence of orchard row canopy discontinuity on irradiance and leaf area distribution iii apple trees. *J. Hortic. Sci. Biotechnol.* **1998**, *73*, 289–297. [CrossRef]