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The Effects of Planting Density, Training System and Cultivar on Vegetative Growth and Fruit Production in Young Mango (*Mangifera indica* L.) Trees

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Abstract: Increasing the planting density of mango orchards appears promising for obtaining higher yields, particularly during the first productive years. However, the challenge is to maintain a good balance between vegetative growth and fruit production in the longer term. The objective of this study was to decipher the effects of planting density, training system and cultivar on young mango trees' growth and production. The experiment, conducted in North Queensland, consisted of five combinations of planting density and training system applied to the cultivars Keitt, Calypso and NMBP-1243. The planting densities were low (208 tree ha^{-1}), medium (416 tree ha^{-1}) and high (1250 tree ha^{-1}). The closed vase conventional training system was applied at each density. Single leader and espalier on trellis training systems were applied at medium and high densities, respectively. The tree canopy dimensions were measured every 6 months from planting, and tree production was recorded from the third to the fifth years after planting. Vegetative growth and fruit production were the results of complex interactions between planting density, training system, cultivar and/or time. The expected increase in orchard yield with higher planting density was observed from the first productive year, despite lower individual tree production at high planting density. Lower vegetative growth and fruit production at high planting density were probably caused by competition between trees. NMBP-1243 and Keitt showed more rapid vegetative growth. Keitt was the most productive cultivar during the first three productive years. The detailed results of this study provide avenues to further explore the behaviour of mango trees at high planting densities.

Keywords: Australia; pruning; temporal changes; tree dimensions; tropical fruit; yield

1. Introduction

Commercial mango (*Mangifera indica* L.) orchards in Australia and other countries are typically managed as large well-spaced trees with planting densities between 69 and 416 tree ha^{-1} [1]. These low and medium planting densities lead to a slow increase in orchard yields during the early productive years and contribute to overall low orchard productivity [2]. The irregular bearing behaviour of most cultivars further reduces productivity [3,4]. Cultivation practises like pruning, pest and disease control and harvest are hampered by large tree size. Improving mango orchard productivity is an important objective to increase growers' income, meet the increasing market demand and address the competition for agricultural land in many countries.

The intensification of mango orchards through increased planting densities, specific tree training and vigour management has been suggested to increase productivity [5]. Based

on the success of orchard intensification in temperate fruit crops such as apple [6], pear [7], cherry [8] and olive [9], we expect orchard intensification in mango to have a similar rapid increase in young orchards' productivity and higher yields in mature orchards.

High-density planting, ranging from about 500 to 3330 tree ha^{-1}, has been investigated for mango orchards for several decades. Early work in Australia [10] with 'Kensington Pride', 'Magovar' and 'Haden' on Tatura trellis at 1666 tree ha^{-1} (1 m × 6 m), 666 tree ha^{-1} (2.5 m × 6 m) and 476 tree ha^{-1} (3.5 m × 6 m) found hyperbolic yield curves with relatively high yield gains followed by yield decline that were intrinsically linked with tree vigour and planting density. Menzel and Le Lagadec [5] reviewed this research and observed diverse results, dependent on the plant material (cultivar and/or rootstock), the techniques investigated and the location of the experiment. They concluded that further research is still required to develop efficient and manageable high-density mango orchards and identified controlling tree size while maintaining sufficient and regular production as the main challenge.

Managing tree vigour can be accomplished by cultural practises such as pruning, canopy training and growth regulators, or by rootstock and scion genetics. Pruning is used to keep mango tree size and shape consistent with the allocated space and to avoid canopy intertwining, shading and yield decline. Moreover, regular pruning of young trees increases the number of terminal shoots, which are the future flowering points in mango [11]. Pruning technique, intensity and timing may affect tree yield. Annual light to medium pruning generally has little or no negative impact on yield, whereas heavy pruning can decrease yield, sometimes for several years [5,12–15]. In low planting density orchards, where mango trees are not space-limited, regular annual pruning effectively avoids yield reduction in mature bearing trees. Delaying annual pruning after harvest to closer to flowering can reduce yield in the following season [16,17].

Tree training is a particular type of canopy management aimed at developing canopy shapes that do not occur naturally. Tree training aims to improve light interception by and distribution within the canopy [18–22], and to reduce vegetative growth for the benefit of fruit production [23–25]. It involves specific pruning and/or limb-bending techniques, in free-standing or trellis-trained trees.

Growth regulators, such as paclobutrazol, are used to control vegetative growth, with expected improvement in flowering and fruiting [26,27]. However, the use of paclobutrazol has been questioned as it represents a risk for human and environmental health through residues in the fruit and contamination in ground and surface waters [28].

Plant genetics, in terms of scion and rootstock genotypes, are also important considerations. Vigorous mango cultivars grow rapidly, and their size is difficult to maintain within the confined space imposed by medium- or high-density planting. Tree production is generally correlated with tree size [5], but some low-vigour cultivars exhibit high yield with small tree size, such as Irwin [29], Keitt [30] and Calypso [31] in Australia, Tommy Atkins in Brazil [32] and Bangalore in India [33]. High-yielding, low-vigour cultivars are more suited for high-density planting [5]. Similarly, rootstocks conferring low vigour and maintaining good yield would also be more suited for high-density planting [34–36].

The influence of these growth management and genetic factors has mainly been studied separately and/or not in the context of high-density orchards [5]. They should, however, be considered together, in a systemic approach, as strong interactions are assumed between plant genetics, environment, training system, canopy management and planting density [5]. These interactions make it difficult to decipher the contribution of each factor separately on tree vigour, canopy development and yield.

The objectives of this study were to experimentally evaluate combinations of planting density, training system and cultivar on tree growth, within the allocated space of the different planting densities and training systems, and fruit production during the first five-year establishment period of a mango orchard. Specifically, we asked the following: how do training system and planting density affect canopy dimensions and yield, and are the responses cultivar-specific?

2. Materials and Methods

2.1. Experimental Site

The experiment was established at the Queensland Department of Agriculture and Fisheries Walkamin Research Station (17°08′17″ S; 145°25′41″ E; elevation 599 masl) in Australia. The location is favourable for mango cultivation with a dry tropical climate with clear alternation of a hot rainy season and a cool dry season, as recorded by a weather station of the Bureau of Meteorology at the site (Figure 1). During the experiment, the average monthly temperature varied between 17.4 °C and 26.9 °C. Annual rainfall ranged from 542 mm in 2016 to 1256 mm in 2018.

The soil is a yellow-to-brown Ferrosol under the Australian Soil Classification, with the local soil type described as Walkamin (Wk) [37]. This soil type is a deeply mottled, yellow-brown pedal clay with a neutral pH, with ferro-manganiferous nodules accumulating throughout its profile [37].
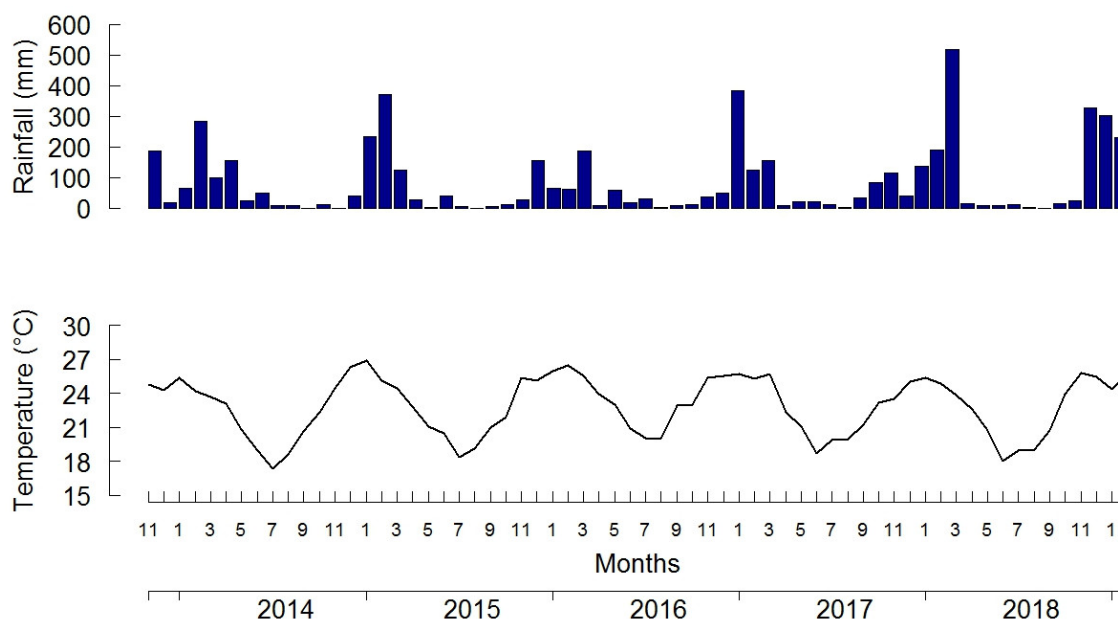
Figure 1. Monthly rainfall and average temperature on the Walkamin Research Station from November 2013 (one month before the experiment planting) to January 2019 (end of the harvest of the third productive year) [38].

The experiment consisted of three primary factors, tree planting density, tree training system and cultivar. Three planting densities were considered: low density (LD: 208 tree ha^{-1}, 8 m × 6 m), medium density (MD: 416 tree ha^{-1}, 6 m × 4 m) and high density (HD: 1250 tree ha^{-1}, 4 m × 2 m). The three training systems were conventional (i.e., closed vase) at all three planting densities, and single leader and espalier on trellis at MD and HD, respectively. The three cultivars were Keitt, Calypso and NMBP-1243.

2.2. Plant Material

The three cultivars were chosen for their anticipated suitability for intensive orchards and their commercial status. Keitt is a Floridian cultivar selected as an open pollinated seedling of Mulgoba with a fast growing, medium-density, open, upright canopy that bears regular, late-season, heavy crops [39]. It is a popular cultivar grown and traded throughout the world. Calypso is an Australian hybrid cultivar between Sensation and Kensington Pride [40] with a compact, low-to-moderate vigour canopy [1,39], regular heavy bearing and mid-season harvest. It represents 24% of Australia's fresh mango production [41]. NMBP-1243 is a recently released Australian hybrid cultivar named 'Yess!' with medium vigour and an open canopy that bears medium-to-heavy early-season crops [42]. All trees

were grafted onto the polyembryonic Kensington Pride rootstock. Trees were planted as single stemmed plants in December 2013 in north–south-orientated rows.

2.3. Training Systems

The conventional training system (Figure 2a) was used in all three planting density treatments. In these trees, the initial cut was made at 50–65 cm above the ground, one week after field planting, to stimulate lateral branching. Two months after field planting, in February, early summer 2014, three to four of the shoots from the first cut were selected as scaffold branches for the closed vase canopies, typical of young conventional trained trees in Australia. Further branching of the scaffold branches was encouraged by tip pruning approximately every two growth units [43–45]. All branches were allowed to grow naturally without any bending. Branches growing across the centre of the tree, dead and diseased branches and the oldest leaves in the centre of the canopies were removed annually to reduce shading and discourage their use as habitats for pests and diseases.
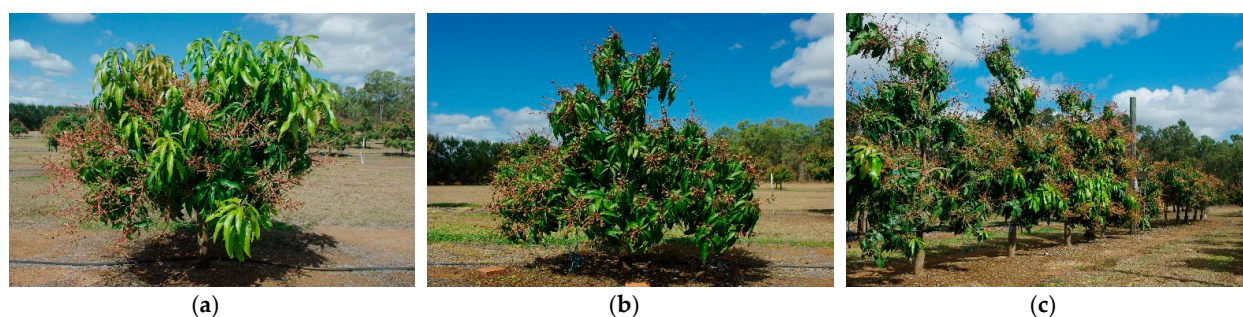

(**a**) (**b**) (**c**)

Figure 2. Canopy shape of mango trees 36 months after planting, trained using (**a**) conventional, (**b**) single leader and (**c**) espalier on trellis methods.

Single leader trees (Figure 2b) were only grown at the medium planting density. These trees were trained to a free-standing, three-dimensional, vertical single leader (central axis). The initial cut was made at 50–65 cm above the ground, one week after field planting, to stimulate lateral branching. Up to five shoots from the first cut were selected. One shoot was left to grow vertically to maintain the central axis of the tree, and the other shoots were bent horizontally with string before they hardened to form the first layer of scaffold branches. The central axis was subsequently cut approximately every 50–60 cm to form additional horizontal scaffold branch layers. Scaffold branches were bent to the horizontal as before. Branching was encouraged in the hardened horizontal scaffold branches by tip pruning at approximately every two growth units [43–45]. This training method resulted in a tree with an overall conical shape which allows better light penetration to the trunk between each horizontal layer of scaffold branches [21]. As the trees aged, the conical canopy shape was maintained through the complete removal of overly dense shoots and vigorous regrowth. Strong vertical shoots, competing with the central leader axis were also cut back to one growth unit.

Espalier-trained trees on trellis (Figure 2c) were only grown at high planting density. Trellises were established prior to planting using treated pine posts to 3.5 m above ground and placed 12 m apart along the planting rows. Galvanised high-tensile wires were attached to posts 0.5 m apart, from a 0.5 m to 3 m height from the ground. Espalier trees were trained to a single vertical central axis. The first cut was made at or just above the lowest trellis wire, 0.5 m from the ground, one week after field planting. A maximum of five shoots from the first cut were retained from the regrowth. One shoot was allowed to grow vertically up to the next wire to maintain a single central axis of the tree. The other branches were bent horizontally in either direction along the row by tying them to the wire before they hardened. These formed the main lateral scaffold branches along the trellis wire. Consecutive terminal growth units from each lateral scaffold branch were bent to the horizontal by tying the shoot loosely to the trellis wire with string until they reached their

allocated space, one metre from the central axis. As the central axis grew vertically, pruning and training in this way was repeated at each wire. During the first two unproductive years after planting, scaffold branches remained unpruned until flowering, at which point the terminal inflorescences were removed to encourage branching shoots on lateral scaffold branches. After harvest, shoots arising from nodes along the lateral scaffold branches were pruned to one or two growth units from the lateral to encourage multiple terminal shoots that had the potential to flower the following season. This pruning strategy was applied each year to maintain the growth of the tree within the allocated space.

For all training systems, there were three main pruning scenarios. The first was 'tree training', which was used early in the trees' development to form the main branch scaffolds. The second was 'inflorescence removal' in the first two years after planting to allow small trees to continue vegetative growth and structural development. Trees began to flower, albeit inconsistently, in August 2014, 9 months after planting. Hence, inflorescences were removed in August 2014 and September 2015. Flowers and fruits were left on the trees from the third year after planting (2016). The third pruning scenario was 'annual pruning' to remove the distal parts of branches and old dried inflorescences to renew the canopy and maintain its shape and dimensions. Annual pruning was carried out immediately after harvest.

2.4. Tree Management

Trees were fertilised and irrigated in accordance with standard Australian mango industry recommendations [45]. Trees at low and medium planting density were irrigated with under-tree sprinklers, and those at high planting density were irrigated with a single line of drippers. All trees received a similar quantity of irrigation water. In the first two years, irrigation was continued throughout the whole year to allow rapid tree growth. From the third year, irrigation was reduced to one watering a month during the winter dormant period, from the end of May until flower bud formation in late July.

In October 2014 and 2015, 100 g of 12-5.2-14.1 NPK fertiliser was applied under the drip line of each tree. From February 2016, 350 g of the same NPK fertiliser was applied in February and June of each year in the same location. The rate of NPK fertiliser was increased in 2018 to 650 g tree^{-1} in February only. In addition, 2 kg of gypsum, 500 g of magnesium sulphate and 10 g of soluble boron (Solubor) were applied four weeks after the February NPK fertiliser. Prior to flowering, trees received a 1% potassium nitrate foliar spray and a 1% foliar spray of boron and zinc, if required as determined by annual leaf analysis. During fruit development, each tree received 500 g of potassium sulphate, applied as two doses three weeks apart. In February 2017 and 2018, 3 g of paclobutrazol (Payback™) was applied to each tree as a soil drench at the base of the trunk, after the first post-pruning vegetative flush had hardened.

2.5. Experimental Design

The experiment was designed as a split-split-plot, with planting density at the main plot level, training system at the sub-plot level and cultivar at the lower sub-sub-plot level. Each sub-plot consisted of five rows: three datum rows, flanked by one guard row on each side. Each datum row (sub-sub-plot) comprised five trees of a single cultivar, three datum trees in the middle and a guard tree at either end, except for high-density espalier plots, which comprised four datum trees and a guard tree at each end. The experimental design was replicated in 6 blocks. Overall, 15 combinations of cultivar × (planting) density × training system were experimentally compared.

2.6. Data Collection

Tree dimensions (tree height, canopy width, canopy length and trunk diameter or circumference (converted to trunk cross-sectional area (TCSA)) were measured for each datum tree in July 2014 (7 months after planting (MAP), TCSA and tree height only), March 2015 (15 MAP), November 2015 (23 MAP), May 2016 (29 MAP), November 2016

(35 MAP), June 2017 (42 MAP), November 2017 (47 MAP) and June 2018 (54 MAP). From 2016, measurements were recorded in May–June, after the vegetative growth period and prior to flowering. Canopy length is defined as the length of the canopy along the planting row, while canopy width is the width of the canopy into adjacent inter-rows. Canopy width and length were not recorded for MD single leader trees at 23 MAP.

TCSA was calculated as a function of trunk diameter (*d*) using

$$TCSA = \pi(d/2)^2 \tag{1}$$

while trees were small and as a function of trunk circumference (*C*):

$$TCSA = C^2/4\pi \tag{2}$$

as the trunk size increased. Trunk diameter and circumference were measured at a point 10 cm above the graft at the same position each measurement time, using a permanent mark on each trunk.

Fruit production per tree (kg tree^{-1}) was recorded for the first three productive seasons, 2016/17 (37 MAP), 2017/18 (49 MAP) and 2018/19 (61 MAP). In 2016/17 and 2018/19, all fruits were counted and weighed at harvest on the datum trees. In 2017/18, tree production was calculated as the total number of fruits harvested from each datum tree, multiplied by the mean individual fruit mass on that tree, determined from 25 randomly sampled fruits. Orchard yield (t ha^{-1}) was calculated by multiplying tree production by the corresponding planting density (tree ha^{-1}).

2.7. Statistical Analyses

Based on the experimental design, the full fixed-effects model comprised terms for planting density (PD), training system (TS) and cultivar (C), and can be expressed as PD + PD:TS + C+ PD:C + D:TS:C. The main effect of training system is not fitted directly in the fixed-effects model as it is nested within planting density.

The change in tree dimensions across the 54 MAP and yield across three productive years were assessed using repeated measures linear mixed models. The fixed-effects model described above was crossed with an additional term representing time (MAP). The full split-split-plot experimental design structure was fitted as the random effects model. This included terms for replicate blocks, the main planting density plots within replicate blocks, and training system sub-plots within planting density plots. For each response variable, an unstructured variance–covariance model was fitted using the ASReml-R package [46] within R [47].

To satisfy the assumption of homogeneity of variance, a log$_{10}$ transformation was required for TCSA and tree height, while the milder square root transformation was applied to canopy length and width. In all analyses, significance testing was performed at $\alpha = 0.05$. To account for the large number of multiple comparisons and to control the familywise error rate, pairwise comparisons were performed using Fisher's protected 95% least significant difference (LSD) with a Bonferroni-adjusted alpha level. With 15 combinations of planting density, training system and cultivar, assessed at 7 time points for tree dimensions and 8 for TCSA, the Bonferroni-adjusted *p*-values were 0.0000092 and 0.000007 respectively. Due to the large number of comparisons and the conservative nature of the Bonferroni adjustment, differences which appeared biologically significant might be reported as not statistically significant.

3. Results

The levels of significance of each factor and their interactions in the repeated measures linear mixed models are given in Table 1. When a factor is included in a significant interaction, its main effect should be considered cautiously.

Table 1. *p*-values associated with all main effects and interactions of planting density, training system, cultivar and time in the analysis related to mango tree vegetative growth, production and orchard yield. TCSA: trunk cross-sectional area at 10 cm above the graft point. Significant *p*-values ($p < 0.05$) are in bold.

Model Terms	TCSA	Tree Height	Canopy Length	Canopy Width	Tree Production	Orchard Yield
Density	**0.001**	0.056	**0.001**	**<0.001**	**<0.001**	**<0.001**
Cultivar	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Density × training	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.108	**0.013**
Density × cultivar	0.375	**0.008**	**0.006**	**0.002**	**<0.001**	**<0.001**
Density × time	**0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
Cultivar × time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.045**
Density × training × cultivar	0.136	**<0.001**	0.722	**0.001**	**0.001**	**<0.001**
Density × training × time	**<0.001**	**<0.001**	**<0.001**	**<0.001**	0.079	**0.011**
Density × cultivar × time	0.260	0.953	**<0.001**	0.106	0.118	0.232
Density × training × cultivar × time	0.136	**<0.001**	**<0.001**	0.236	**0.022**	0.343

The main effects and interaction of cultivar × time were significant for all variables studied, as was the interaction of density × time. In contrast, the three-way interaction of density × cultivar × time was only significant for canopy length, and not the other variables, indicating, for each cultivar, that only changes in canopy length over time were affected by planting density. The variables TCSA, canopy width and orchard yield did not have a significant four-way interaction but did have a significant three-way interaction of density × training × time. TCSA was also influenced by the two-way interaction of cultivar × time. Canopy width and orchard yield were influenced by the three-way interaction of density × training × cultivar.

The variables tree height, canopy length and tree yield did have a significant four-way interaction of density × training × cultivar × time. To avoid long detailed descriptions and redundancy, we have not explicitly described the four-way interactions. The interaction of density × training × time is described for each cultivar as it provides a better understanding of the factor effects on the variables for each cultivar. The values presented in the text and in the figures are the predicted means from the analysis.

3.1. Trunk Cross-Sectional Area (TCSA)

The four-way interaction of density × training × cultivar × time, and the three-way interactions involving cultivar, were not significant for TCSA (Table 1). However, the interaction of density × training × time was significant ($p < 0.001$, Table 1), as was the interaction between cultivar and time ($p < 0.001$, Table 1).

Changes in TCSA between 7 and 54 MAP differed between the combinations of planting density and training system (Figure 3a), with significant increases between successive measurements of each combination, between 7 and 42 MAP. Between 42 and 54 MAP, significant increases between successive measurements were only observed in HD and MD conventional trees. Increases in TCSA were smaller and not significant between 42 and 47 MAP in the LD conventional, MD single leader and HD espalier trees, but were significant between 47 and 54 MAP for MD single leader and HD espalier trees, but not for LD conventional trees.

The effect of the planting density and training system on TCSA followed two main trends (Figure 3a): (i) at medium and high planting density, TCSA was higher for conventional trees than for single leader and espalier trees, respectively, and (ii) TCSA was higher for LD and MD conventional trees than for HD conventional trees, and higher for MD single leader trees than for HD espalier trees. There was no significant difference in TCSA between the combinations of planting density and training system at 7, 15 and 23 MAP, after which three groups appeared. (i) The TCSA of LD and MD conventional

trees increased similarly and rapidly. (ii) The TCSA of HD espalier trees increased the least, and by 29 MAP, was significantly lower than that of LD and MD conventional trees. (iii) The changes in the TCSA of HD conventional and MD single leader trees were similar, as were those between the two previous groups. At 47 and 54 MAP they were significantly higher than the TCSA of HD espalier trees, but not significantly lower than LD conventional and MD conventional trees. At 54 MAP, TCSA was 69.3 cm^2 in MD conventional trees, 69.0 cm^2 in LD conventional trees, 58.5 cm^2 for MD single leader trees, 57.5 cm^2 for HD conventional trees and 47.4 cm^2 for HD espalier trees.
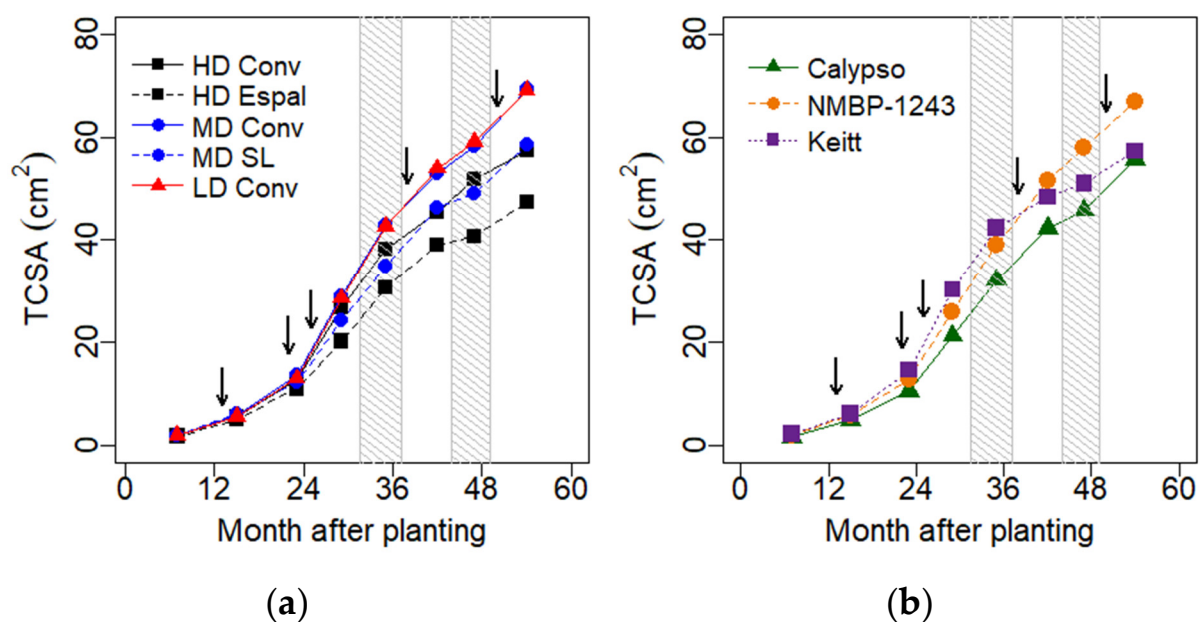

(a)   **(b)**

Figure 3. (**a**) The interaction between planting density, training system and time for trunk cross-sectional area (TCSA) and (**b**) the interaction between cultivar and time for TCSA. No measure of variability is presented as the data were analysed on the log_{10} scale, and the back-transformed means are presented. HD, MD and LD: high, medium and low planting density, respectively; Conv, Espal and SL: conventional, espalier, and single leader training systems, respectively. The arrows indicate pruning events. The shaded areas indicate reproductive periods from flowering to harvest.

The interaction of cultivar × time (Figure 3b) showed a similar pattern of significant increases in TCSA for sequential measurement in NMBP-1243 and Calypso. The TCSA of Keitt was higher than that of the other two cultivars up to 35 MAP, and significantly higher than that of Calypso. Between 42 and 47 MAP, the TCSA of Keitt was intermediate between Calypso and NMBP-1243. At 54 MAP, the TCSA of Keitt (57.3 cm^2) was not significantly different to that of Calypso (55.7 cm^2) but was significantly lower than that of NMBP-1243 (66.9 cm^2). The tCSA of Calypso was also significantly lower than that of NMBP-1243.

3.2. Tree Height

The repeated measures analysis of tree height showed a significant four-way interaction of density × training × cultivar × time ($p < 0.001$, Table 1).

The increases in the tree height of NMBP-1243 were significant between sequential measurements from 7 to 35 MAP for all combinations of planting density and training system, despite a lower increase between 15 and 23 MAP due to inflorescence removal and pruning at 21 MAP (Figure 4a). After the first harvest, trees were heavily pruned at 38 MAP, which decreased tree height in the conventionally trained trees of all planting densities, but the decrease was only significant in the LD conventional trees at 42 MAP (2.35 to 2.05 m). After 42 MAP, tree heights were generally stable for the conventionally trained trees, with only small increases in the LD and MD trees, despite pruning at 50 MAP after the second harvest. The tree heights in the HD espalier and MD single leader trees did not decrease

after the first harvest and pruning. The height of HD espalier trees was consistent from 35 to 54 MAP, ranging from 2.62 to 2.77 m. The height of MD single leader trees fluctuated slightly from 35 to 54 MAP, with values ranging from 2.38 to 2.52 m. In particular, during the period between 42 and 47 MAP, which spanned flowering and fruit growth, the mean tree height decreased despite the trees not being pruned. The drop in height was related to the bending of the highest vertical axes under the weight of the fruit. Young trees are particularly prone to this phenomenon.

(**a**)   (**b**)   (**c**)
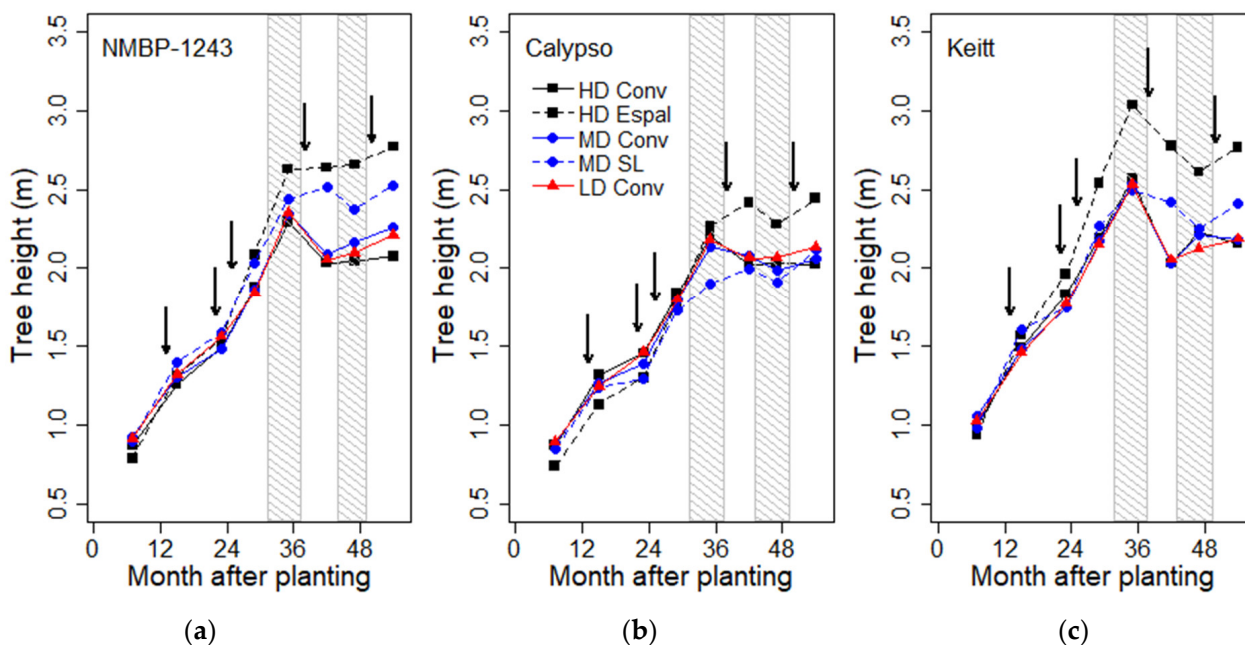
Figure 4. The effect of planting density and training system on changes in mean tree height for three mango cultivars (NMBP-1243 (**a**), Calypso (**b**), Keitt (**c**)) during the first 54 months after planting. No measure of variability is presented as the data were analysed on the $\log_{10}$ scale, and the back-transformed means are presented. HD, MD and LD: high, medium and low planting density, respectively; Conv, Espal and SL: conventional, espalier and single leader training systems, respectively. The arrows indicate pruning events. The shaded areas indicate reproductive periods from flowering to harvest.

NMBP-1243's mean tree height was not significantly different between the training systems up to 42 MAP (Figure 4a), when the HD espalier trees were significantly higher than trees of the three conventional training systems at 42, 47 and 54 MAP. MD single leader trees were also significantly higher than trees of the three conventional training systems at 42 MAP.

The tree height in Calypso significantly increased between sequential measurements from 7 to 35 MAP for all training systems, except for MD single leader trees, whose height did not increase significantly between 29 and 35 MAP (Figure 4b). As with NMBP-1243, the increase was smaller between 15 and 23 MAP due to inflorescence removal and pruning at 21 MAP. After the first harvest, and pruning at 38 MAP, tree heights decreased slightly in the conventionally trained trees of all planting densities before stabilising around 2.05 m from 42 to 54 MAP. The height of HD espalier and MD single leader trees increased irregularly and not significantly from 35 to 54 MAP, with a small decrease from 42 to 47 MAP due to the bending effect of fruit load on the highest vertical axes. Between 35 and 54 MAP, Calypso tree height increased significantly only from 47 to 54 MAP (1.91 to 2.12 m) in the MD single leader trees.

At 7 MAP, the height of Calypso HD espalier trees was significantly lower than that of trees of the three conventional training systems (Figure 4b). For each measurement between 15 and 35 MAP, tree height did not differ significantly between combinations of

planting density and training system. At 42 MAP, HD espalier trees were significantly taller (2.42 m) than LD (2.07 m) and HD (2.03 m) conventional trees, and MD single leader trees (1.99 m). The tree height of MD conventional trees (2.09 m) was intermediate. At 54 MAP, HD espalier trees were significantly taller (2.44 m) than MD (2.06 m) and HD (2.03 m) conventional trees. The mean tree heights of MD single leader (2.12 m) and LD conventional (2.14 m) trees were intermediate.

The increases in tree height for Keitt were significant between sequential measurements from 7 to 35 MAP (Figure 4c), after which tree heights generally decreased or fluctuated due to pruning at 38 MAP and fruit load, similar to the other cultivars. The tree heights in MD single leader and HD espalier trees decreased from 35 to 47 MAP (2.50 m to 2.25 m for MD single leader trees; 3.04 m to 2.61 m for HD espalier trees). The tree height of the conventional trees in the three planting densities decreased sharply, but not significantly, from pruning at 38 MAP to 42 MAP (2.54 m to 2.04 m on average). The only significant increase in tree height was in HD conventional trees (2.03 to 2.24 m) between 42 and 47 MAP.

Keitt trees were taller in the HD espalier system than all other training × density systems from 23 MAP, with significant differences with the three conventional training systems at 29 MAP, 42 MAP and 54 MAP. The tree height of MD single trees was intermediate between 42 and 54 MAP.

3.3. Canopy Length

Canopy length measured along the row was one of the first canopy dimensions to be limited by the allocated space for trees. This was especially the case in the HD planting. A significant four-way interaction of density × training × cultivar × time was detected for canopy length ($p < 0.001$, Table 1).

The increase in canopy length for NMBP-1243 was significant in the HD espalier trees from 15 to 29 MAP, after which it stabilised at approximately 2.25 m until 54 MAP (Figure 5a). In the MD single leader trees, canopy length increased significantly from 15 to 29 MAP and from 29 to 35 MAP (no data were recorded at 23 MAP for this training system). After 35 MAP, canopy length stabilised at an average of 2.53 m, with a slight decrease between 42 and 47 MAP, associated with the bending of branches due to heavy fruit load on horizontal branches. In NMBP-1243 LD, MD and HD conventional training systems, canopy length decreased slightly, but not significantly, between 15 and 23 MAP (pruned 21 MAP) and increased significantly (from 0.82 m to 1.90 m on average) from 23 to 29 MAP. From 29 MAP, the canopy length of the HD conventional trees stabilised at an average of 1.97 m, with slight fluctuations related to pruning events at 38 and 50 MAP. In contrast, the canopy length of LD and MD conventional trees continued to increase significantly from 29 to 35 MAP, after which they decreased to 42 MAP, due to the pruning event at 38 MAP; they then increased from 42 to 54 MAP.

The canopy length of NMBP-1243 HD espalier trees was significantly higher at 15 MAP (1.67 m) and 23 MAP (1.87 m) than that in the other planting density × training system combinations (Figure 5a). At 29 and 35 MAP, there was no significant difference in canopy length between any of the planting density × training system combinations. The canopy length in HD conventional trees was significantly shorter than that of MD single leader trees at 42 and 47 MAP and that of MD conventional trees at 47 MAP. At 54 MAP, it was significantly shorter (1.94 m) than that of both MD training systems (2.63 m for conventional trees and 2.64 m for single leader trees) and LD conventional trees (2.50 m).

The canopy length of Calypso followed a similar trend over time to NMBP-1243 but with smaller means (Figure 5b). The canopy length of the HD espalier trees increased significantly between successive measurements from 1.17 m at 15 MAP to 2.15 m at 29 MAP, before stabilising at an average of 2.15 m. The small decrease in canopy length between 29 and 35 MAP and stability between 42 and 47 MAP, when no pruning occurred, was related to the bending of horizontal branches with fruit load. In the MD single leader trees, canopy length increased significantly from 15 (0.98 m) to 35 (1.82 m) MAP and then sta-

bilised at an average of 1.96 m. Conventional Calypso trees in all planting densities initially decreased in canopy length from 15 to 23 MAP (pruned 21 MAP) and increased significantly from 23 to 29 MAP. In the LD and MD conventional trees, and canopy length continued to increase significantly up to 35 MAP, after which regular, smaller and non-significant increases in canopy length were measured between successive measurements (from 1.87 m to 2.19 m in LD conventional trees, and from 1.94 m to 2.14 m in MD conventional trees). In contrast, the canopy length of HD conventional trees remained reasonably consistent after 29 MAP at an average of 1.86 m, due to the limited allocated space of the HD planting.
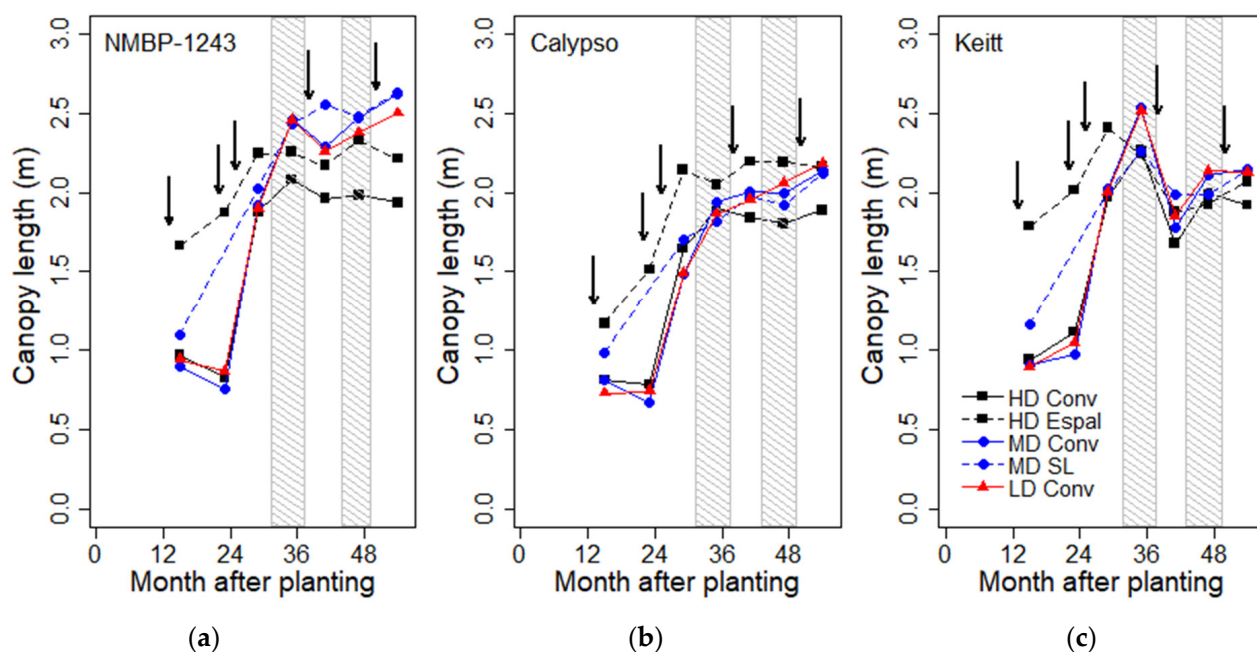
Figure 5. The effect of planting density and training system on the mean canopy length of three mango cultivars (NMBP-1243 (**a**), Calypso (**b**), Keitt (**c**)) during the first 54 months after planting. No measure of variability is presented as the data were analysed on the square root scale, and the back-transformed means are presented. HD, MD and LD: high, medium and low planting density, respectively; Conv, Espal and SL: conventional, espalier and single leader training systems, respectively. The arrows indicate pruning events. The shaded areas indicate reproductive periods from flowering to harvest.

In the HD espalier Calypso trees, the canopy lengths at 15, 23 and 29 MAP were significantly larger than those in the three conventional training systems (Figure 5b). From 35 MAP, no significant difference was detected between the combinations of planting density and training system.

The canopy lengths in Keitt trees followed a similar trend over time to that described for NMBP-1243 and Calypso, where they increased up to 29 or 35 MAP and then fluctuated between the following dates. In the HD espalier Keitt trees, the only significant change in successive measurements was a decrease in length from 35 to 42 MAP (2.25 m to 1.88 m, Figure 5c) due to pruning at 38 MAP. The non-significant decrease between 29 and 35 MAP, when no pruning occurred, was related to branch bending with fruit load. The overall change in the canopy length of HD espalier trees from 15 to 54 MAP (1.79 m to 2.07 m) was not significant. The canopy length of the Keitt MD single leader trees increased significantly in a linear trend from 15 to 35 MAP, where it reached a maximum at 2.26 m. From 35 MAP to 54 MAP, the tree canopy length fluctuated, with no significant differences between successive measurements. The Keitt canopy length in the LD, MD and HD conventional training system followed a similar pattern over time, with a small increase from 15 to 23 MAP (pruned 21 MAP), before increasing significantly to 35 MAP when they reached a maximum, between 2.27 m (HD conventional trees) and 2.54 m (MD conventional

trees). The increase between 23 and 29 MAP was significant for the three conventional training systems. In contrast, the increase between 29 and 35 MAP was significant only for LD (1.99 m to 2.52 m) and MD conventional trees (2.03 m to 2.54 m) that were not limited by their allocated space. The canopy length of the LD, MD and HD conventional trees decreased significantly between 35 and 42 MAP (from 2.44 m to 1.77 m on average). Tree canopy length then increased significantly from 42 to 47 MAP (2.08 m) and remained constant in the LD and MD conventional trees or decreased slightly in the HD conventional trees up to 54 MAP due to pruning at 50 MAP. The decrease in canopy length observed between 35 and 42 MAP for all the combinations of planting density and training system was related to heavy pruning at 38 MAP.

At 15 MAP, the canopy length of Keitt HD espalier trees was significantly larger (1.79 m) than that of the trees of all other combinations of planting density and training system (0.98 m on average, Figure 5c). This significant difference was also observed at 23 MAP. At 29 MAP, the canopy length of HD espalier trees was only significantly longer than that of HD conventional trees. At all subsequent measurements, there was no significant difference between the combinations of planting density and training system.

3.4. Canopy Width

The four-way interaction of density × training × cultivar × time for canopy width was not significant ($p = 0.236$, Table 1). The three-way interactions of density × training × time ($p < 0.001$, Table 1) and density × training × cultivar ($p = 0.001$, Table 1) were significant.

The interaction of density × training × time (Figure 6a) showed a similar evolution of canopy width for the five combinations of planting density and training system. The general trend was an increase over time, with significant differences between successive measurements from 15 to 35 MAP when it reached a maximum width of 1.51 m for HD espalier trees and 2.16 to 2.31 m for the four other combinations of planting density and training system. Canopy width then decreased significantly (except for MD single leader trees) between 35 and 42 MAP following pruning at 38 MAP. Changes in canopy width showed different patterns between 42 and 54 MAP. It remained stable for MD single leader trees or fluctuated around an average value for HD conventional trees, with significant differences between successive measurements. It increased significantly between 42 and 54 MAP for LD and MD conventional trees and for HD espalier trees.

The canopy width of HD espalier trees was consistently and significantly narrower than that of the four other combinations of planting density and training system (Figure 6a). The canopy widths of these four combinations were not significantly different up to 47 MAP. At 54 MAP, the canopy width of HD conventional trees (1.86 m) was significantly lower than that of LD (2.17 m) and MD (2.21 m) conventional trees, likely because of more intense pruning at 50 MAP.

The interaction between planting density, training system and cultivar showed that the cultivar affected tree canopy width for each combination of planting density and training system (Figure 6b). In all cultivars, tree canopies were significantly narrower in the HD espalier than in the other systems. In the HD espalier trees, the differences in canopy width between cultivars were small, although significant between Keitt (0.93 m) and NMBP-1243 (1.10 m). The canopy widths of the four other combinations of planting density and training system differed among cultivars. The canopy width of NMBP-1243 trees was significantly larger than that of Calypso in all conventional training systems and MD single leader trees.
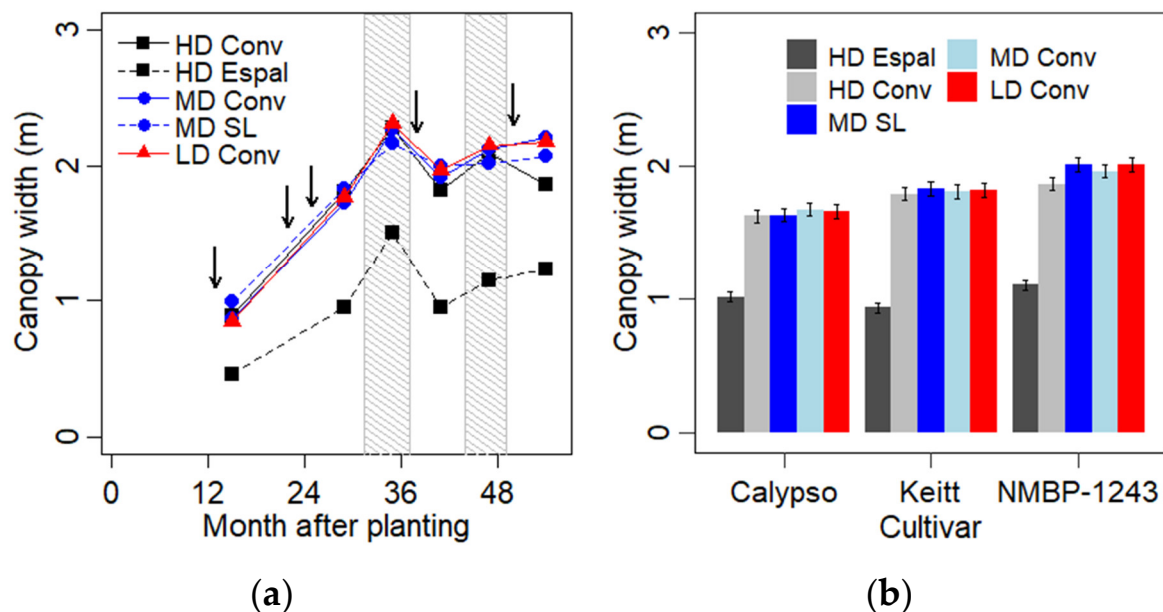
(a)   **(b)**

Figure 6. Three-way interactions between (**a**) planting density, training system and time and (**b**) planting density, training system and cultivar for tree canopy width. No measure of overall variability is presented in graph (**a**) as the data were analysed on the square root scale, and the back-transformed means are presented. On graph (**b**), individual error bars are back-transformed and represent ± 1 standard error. HD, MD and LD: high, medium and low planting density, respectively; Conv, Espal and SL: conventional, espalier and single leader training systems, respectively. On graph (**a**), the arrows indicate pruning events, and the shaded areas indicate reproductive periods from flowering to harvest.

3.5. Tree Production

The repeated measures analysis of tree production showed a significant four-way interaction of density × training × cultivar × time (p = 0.022, Table 1). Fruit production (kg tree^{-1}) in NMBP-1243 LD and MD conventional trees and in MD single leader trees increased in a similar pattern over time (Figure 7a). Increases in production between years 3 and 4 were significant but not between years 4 and 5. In contrast, the production increases in HD espalier trees were more linear from years 3 to 5, with a significant difference between years 3 and 5 only. The production of HD conventional trees stagnated between years 4 and 5 and was not significantly different from that of year 3, despite an increase from 2.5 to 14.8 kg tree^{-1}.

In year 3, NMBP-1243 tree production was not significantly different between the combinations of planting density and training system (Figure 7a), ranging from 0.8 kg tree^{-1} in the LD conventional training system to 4.0 kg tree^{-1} in the MD single leader training system. The ranking of tree production among combinations of planting density and training system was similar in years 4 and 5. The highest production was in the MD single leader training system (29.0 and 37.5 kg tree^{-1} in years 4 and 5, respectively). The lowest production was in the HD espalier trees in year 4 (14.1 kg tree^{-1}) and the HD conventional trees in year 5 (14.8 kg tree^{-1}). Fruit production per tree in both HD training systems was significantly lower than that of the MD single leader training system in years 4 and 5.

The fruit production of Calypso HD espalier and LD, MD and HD conventional trees followed a similar trend between years 3 and 5 (Figure 7b). Increases in production were significant between years 3 and 4, followed by a smaller non-significant increase between years 4 and 5. Annual production increases were smaller for both HD training systems than for the LD and MD conventional systems. The fruit production of MD single leader trees increased linearly from year 3 to 5, but only significantly between years 3 and 5.
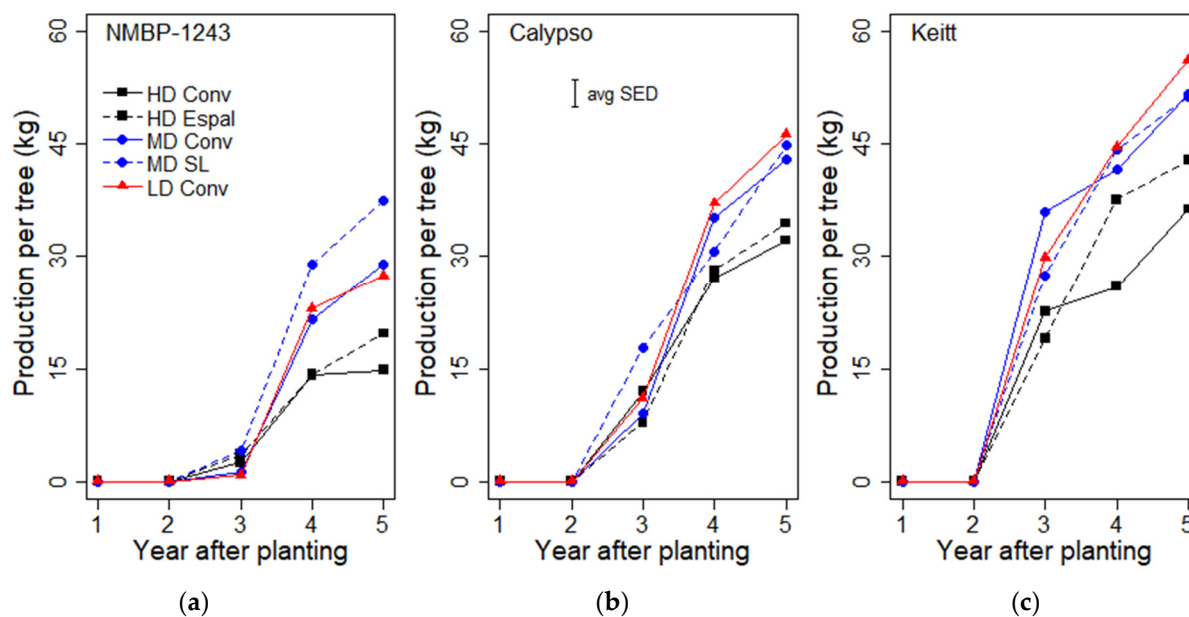
Figure 7. The effect of planting density and training system on the tree production of three mango cultivars (NMBP-1243 (**a**), Calypso (**b**), Keitt (**c**)) during the five first years after planting. The overall average standard error of the difference (avg SED) is given on the centre graph only. HD, MD and LD: high, medium and low planting density, respectively; Conv, Espal and SL: conventional, espalier and single leader training systems, respectively.

Within each year, there was no significant difference in Calypso production per tree between combinations of planting density and training system (Figure 7b). The tree production values of the two HD training systems at year 5 were not significantly different from those of any of the treatments in year 4. In year 3, production was lowest (7.8 kg tree^{-1}) in HD espalier trees and highest (17.8 kg tree^{-1}) in MD single leader trees. In years 4 and 5, the highest production was in LD conventional trees (37.1 and 46.3 kg tree^{-1}, respectively), and the lowest production was in HD conventional trees (27.1 and 32.2 kg tree^{-1}, respectively).

Keitt HD and MD conventional trees showed a small non-significant increase in production between years 3 and 4, and a larger non-significant increase between years 4 and 5 (Figure 7c). The increase between years 3 and 5 was significant. The production changes in LD conventional, HD espalier and MD single leader trees were similar over years 3, 4 and 5, with a large significant increase from year 3 to 4, followed by a smaller and non-significant increase from years 4 to 5.

The two HD training systems had the lowest production for Keitt each year (Figure 7c). In year 3, tree production in the HD espalier training system (19.0 kg tree^{-1}) was significantly lower than that in the LD conventional (29.9 kg tree^{-1}) and MD conventional (36.0 kg tree^{-1}) training systems. The ranking of tree production was similar between the combinations of planting density and training system in years 4 and 5, where tree production in the HD conventional training system (26.0 and 36.4 kg tree^{-1}, respectively) was significantly lower than that of the LD conventional (44.6 and 56.3 kg tree^{-1}, respectively), the MD single leader (44.3 and 51.3 kg tree^{-1}, respectively) and the MD conventional (41.7 and 51.7 kg tree^{-1}, respectively) training systems.

3.6. Orchard Yield

The four-way interaction of density × training × cultivar × time was not significant for orchard yield ($p = 0.343$, Table 1). However, there were significant three-way interactions of density × training × time ($p = 0.011$, Table 1) and density × training × cultivar ($p < 0.001$, Table 1).

The interaction of density × training × time showed that the increase in orchard yield averaged over the three cultivars differed in relation to the planting density during the

three first productive years (Figure 8a). Orchard yield did not increase significantly in the LD conventional training system between years 3 and 5 (Figure 8a). For the two MD training systems, the increases in orchard yield were only significant between years 3 and 5. In contrast, the two HD training systems showed a significant increase in orchard yield between years 3 and 4, but not between years 4 and 5.
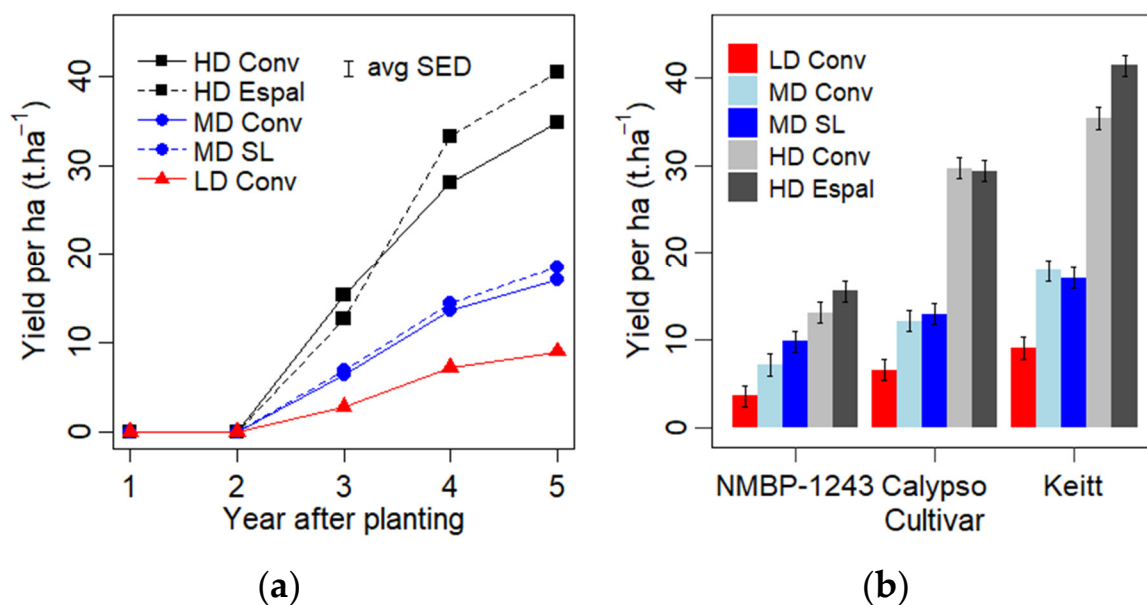

(a)　　　　　　　　　　　　　　　　　　　　　　　　(b)

Figure 8. Three-way interactions for orchard yield between (**a**) planting density, training system and time and (**b**) planting density, training system and cultivar. HD, MD and LD: high, medium and low planting density, respectively; Conv, Espal and SL: conventional, espalier and single leader training systems, respectively. Avg SED in graph (**a**): average standard error of the difference; error bars in graph (**b**) represent $\pm$ one standard error.

In each year, orchard yields were lowest in the LD planting, highest in the HD planting and intermediate in the MD planting (Figure 8a). The training system did not significantly affect orchard yield in the MD or HD planting. During the first year of production (year 3), orchard yield was significantly higher in the two HD training systems (15.4 t ha^{-1} for conventional and 12.7 t ha^{-1} for espalier) than in the LD conventional training system (2.9 t ha^{-1}). Orchard yield was significantly higher in the HD conventional system than in the two MD training systems (6.4 t ha^{-1} for conventional and 6.9 t ha^{-1} for single leader). In years 4 and 5, orchard yields were significantly higher in the two HD training systems, with year 5 yields of 35.7 t ha^{-1} in the HD conventional system and 40.4 t ha^{-1} in the HD espalier system, compared to 9.0 t ha^{-1} in the LD conventional system, 17.2 t ha^{-1} in the MD conventional system and 18.6 t ha^{-1} in the MD single leader system. At year 5, the orchard yields of the two MD training systems were also significantly higher than that of the LD conventional training system.

The interaction of density $\times$ training $\times$ cultivar (Figure 8b) showed that the effects of the combinations of planting density and training system on orchard yield were similar for Keitt and Calypso, and differed for NMBP-1243. For Keitt and Calypso, the orchard yields in the MD conventional and single leader systems were similar, about 2.0 times the orchard yield in LD conventional system. Orchard yield in the HD espalier system was significantly higher than that in the HD conventional system for Keitt, whereas it was similar for Calypso. Orchard yields in HD training systems were between 3.9-fold and 4.6-fold those of the LD conventional system for these two cultivars. On the contrary, the orchard yield of NMBP-1243 showed a regular increase from the LD conventional system to the MD conventional, MD single leader, HD conventional and HD espalier systems (Figure 8b). The differences were significant between the non-consecutive means of the

combinations of planting density and training system. For example, orchard yield in the MD single leader system differed significantly from that in the LD conventional and HD espalier systems. For NMBP-1243, orchard yield in the MD training systems varied between 2.0 times and 2.7 times the orchard yield in the LD conventional system. For the HD training systems, this ratio was between 3.7-fold and 4.4-fold. This result indicated that the decrease in individual tree production in the HD training systems supported by the analysis of the density × training × time interaction (Figures 8a and 9) affected the three cultivars similarly.
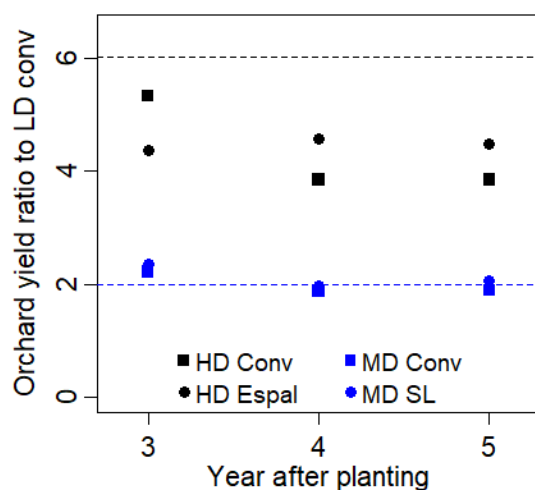
Figure 9. Ratios of orchard yield for combinations of medium and high planting densities and training systems to low-density conventional systems orchard yield during three first productive years after planting. (Conv, Espal and SL: conventional, espalier and single leader training systems, respectively; HD, MD and LD: high, medium and low planting density, respectively). Ratios of MD and HD to LD planting density are represented by blue (MD) and black (HD) horizontal dashed lines.

The average orchard yield of NMBP-1243 over the three first productive years was significantly lower than that of Calypso and Keitt in the HD conventional and HD espalier systems, and in the MD conventional system (Figure 8b). In the LD conventional and MD single leader systems, NMBP-1243's orchard yield was only significantly lower than that of Keitt.

An expected consequence of increasing planting density is a proportional increase in orchard yield. In this experiment, the MD planting density was 2-fold and the HD planting density was 6-fold that of the LD planting density. During the first three productive years, the average orchard yield of the two MD training systems was between 1.9-fold and 2.4-fold that of the LD training system, and the average orchard yield of the two HD training systems was between 3.8- and 5.3-fold that of the LD training system (Figure 9). These latter data showed that the increase in orchard yield was lower than expected in the HD training systems. This is supported by the lower individual tree production in the two HD training systems (Figure 7).

4. Discussion

This study provided original and detailed results on the effects of cultivar, planting density and training system on changes in tree dimensions and tree production during the first five years after planting. During this period, trees are establishing and growing into their allocated space, with the first three years being particularly important for high-density orchards. Tree branch and canopy training during the establishment period is important as it sets the structure for the future shape of the tree, which has a direct influence on young and adult trees' production and performance in an adult orchard.

4.1. Vegetative Growth and Production of Young Mango Trees Are Shaped by Complex Interactions between Planting Density, Training System and Cultivar

The six studied variables had between one and three significant four-way and/or three-way interactions between planting density, training system, cultivar and/or time (Table 1). In particular, time was involved in these high-order interactions for the six studied variables, indicating that the other factors involved in the interaction had specific effects on the changes over time in the variables.

The four-way interaction and the three-way interaction of density × cultivar × time were not significant for the variables TCSA, canopy width and orchard yield (Table 1), indicating that for each cultivar, the planting density did not affect the changes over time in these three variables. However, the interaction of density × training × time was significant for these three variables (Table 1; Figures 3a, 6a and 8a), indicating that their changes over time differed between conventional and non-conventional (single leader and espalier) training systems at medium and high planting density. For example, the changes in canopy width over time were similar between MD conventional and single leader trees, while canopy width was constantly and significantly lower for espalier trees at HD (Figure 6a).

The interaction of density × training × time, which was included in the significant four-way interactions for the variables tree height, canopy length and tree production, was a consequence of the differences in pruning and training strategies between the single leader, espalier on trellis and conventional training systems. These differences had consequences for vegetative growth and fruit production, as discussed below.

4.2. Effects of Planting Density, Training System and Cultivar on Changes in Tree Dimensions of Young Mango Trees

The variables tree height, canopy length and canopy width must be considered differently to TCSA as they are directly affected by the experimental training and pruning strategies, the more or less vigorous vegetative response of each cultivar, and the negative effect of reproduction on vegetative growth [48–50]. The significant four-way interaction for tree height and canopy length and three-way interaction for canopy width were consequences of the controlled (pruning and training strategies) and uncontrolled (cultivar vigour, effect of reproduction) sources of variation in tree dimensions.

The direct effect of training and pruning strategies on tree dimensions was clearly illustrated by HD espalier trees, in which the strategy was to produce a planar tree that filled the 2 m × 3 m space as rapidly as possible by training a central leader vertically and the branches horizontally along the trellis wires. This strategy produced (i) a rapid growth in height, up to 2.5 to 3.0 m in three years, higher than the other training systems (Figure 4); (ii) a rapid growth in canopy length along the row up to 2 m from 29 MAP, after which it was maintained as neighbour trees touched each other in the row (Figure 5); and (iii) a final canopy width of about 1 m, which was significantly narrower from the first year than in the other training systems (Figure 6). The growth in tree height, canopy length and width were remarkably similar for conventional trees. However, the canopy length and width of the HD trees were maintained at about 2 m from 29 MAP when neighbour trees touched each other in the row. In the MD and LD conventional systems, trees' canopy length and width were allowed to expand slowly, as the available space was larger. The growth in tree height, canopy length and width for MD single leader trees was similar to that of conventional trees, with a more rapid increase in canopy length due to the bending of the basal-layer branches to the horizontal. In addition, the canopy length in the MD single leader system was restricted in length at the bottom to allow access to the top of the trees for bending, pruning and harvesting from ladders. Single leader tree height was maintained between 2.0 m and 2.5 m depending on the cultivar.

The training strategies applied in this experiment were combinations of pruning and bending, two practices affecting tree vegetative growth in a cultivar-specific way [51]. In mango, pruning is a rapid trigger (1–3 weeks in favourable conditions [52]) for bud burst and vegetative growth [53,54]. This response depends on the pruning characteris-

tics. Persello et al. [55] demonstrated that the number of new growth units increases with pruning intensity (biomass of leaves and wood removed compared to canopy volume) and pruning severity (distance, in number of growth units, between the axis apex and the pruning point). Several aspects of vegetative growth are affected by pruning, such as the number of new growth units, their individual length and the rhythm of vegetative growth. This vegetative response is cultivar-specific and temperature-responsive in mango [29,53,56]. Consequently, pruning has a direct and immediate effect on decreasing canopy dimensions, and it stimulates a complex vegetative response, increasing canopy dimensions in a few weeks according to the pruning characteristics, the cultivar and the period of pruning.

From the first fruit production, we could assume that reproduction (flowering and fruiting) had a negative effect on changes in canopy dimensions over time. This is related to the costs of reproduction [57], which express that the plant's investment in reproduction has a negative effect on subsequent vegetative growth. The costs of reproduction have been demonstrated at different scales in mango trees, from the terminal growth unit to the whole tree, and they are cultivar-specific [50]. Hormones and carbohydrates are involved in the setting up of the costs of reproduction at the scale of the mango growth unit [58]. The costs of reproduction have not been characterised yet for the three studied cultivars, and it was not possible to assess the effects of their occurrence or intensity in the changes observed in tree dimensions. But they probably contributed, along with the vegetative response to pruning, to the observed changes between 35 and 54 MAP.

Growth in TCSA over time was also affected by the same factors (pruning and training strategies, cultivar-specific vegetative response to these strategies, reproduction), but the effects of pruning and training were indirect as the trunk was not pruned, just the canopy. TCSA is a cumulative variable that is allometrically related to the tree's overall vegetative growth for mechanical support and hydraulic conductance reasons [59–61]. However, growth in the cross-sectional area of the trunk or branches can be influenced by processes that reduce tree growth or divert carbohydrate availability, such as fruit load [62] or competition with neighbour trees [59,63]. In this study, TCSA was the only variable with just one significant three-way interaction (density × training × time), and no four-way interaction. The factor cultivar was involved in a two-way interaction with time (Table 1, Figure 3b). The effects of planting density and training system on TCSA changes over time were therefore not affected by the cultivar, and each cultivar had specific TCSA changes. The three-way interaction showed that the planting density negatively affected TCSA changes over time after 23 MAP. TCSA evolved more rapidly for conventionally trained trees than for non-conventionally trained trees at MD and HD (Figure 3a). This latter trend became significant at 29 MAP, before the first fruit production, suggesting that the differences were related to differences in vegetative growth or to above- and below-ground competition between trees, and were not related to fruit production.

The competition between trees could explain the slower increase in TCSA for HD trees that began to touch each other on the row by 29 MAP (NMBP-1243, Keitt, Calypso conventional) or 35 MAP (Calypso espalier). MD conventionally trained trees were not as constrained by neighbour trees as the HD trees during the experiment, and their TCSA was similar to that of LD trees. The difference in TCSA between conventionally and non-conventionally trained trees at MD and HD could denote a less dense canopy in the non-conventional trees, which could not be evidenced by the measured tree dimensions. Fruit load may have contributed to reduced TCSA growth during the second productive year (42 to 47 MAP) in the single leader and espalier trees (Figure 3a) for Keitt and Calypso (Figure 3b), as they were highly productive in these training systems (Figure 7) and may have had less dense canopies. Similarly, the slower TCSA growth of Keitt compared with Calypso and NMBP-1243 from 35 MAP could be related to the high fruit production of this cultivar during the first productive year (Figure 7 and discussed below).

The four vegetative growth variables showed that Calypso developed more slowly than Keitt and NMBP-1243 during the first 2.5 years after planting (29 MAP). For example, the canopy length of Calypso HD espalier trees was shorter than that of Keitt and NMBP-

1243 trees at 15 and 23 MAP (Figure 5), and the TCSA of Calypso trees was lower than that of Keitt and NMBP-1243 trees up to 35 MAP (Figure 3b). At 29 MAP, just before the first productive period, the allocated space in the row for HD trees (2 m) was reached for all cultivars (Figure 5). Annual post-harvest pruning was then sufficient to maintain the tree dimensions up to year 5 after planting. HD espalier Keitt trees developed rapidly in height, reaching 3 m at year 3 compared to about 2.5 m for the two other cultivars, suggesting that this cultivar has vigorous vertical growth when trained on a trellis.

4.3. Effects of Planting Density, Training System and Cultivar on Tree Production and Orchard Yield of Young Mango Trees

The potential production of a mango tree is related to tree size and to the number of terminal growth units, which depend on the cultivar, training system and pruning strategy. These factors also influence the morphology, position and age of terminal growth units at the time of floral induction, and therefore, their probability of flowering and fruiting [50,54,64,65]. With such intertwined processes of canopy management, cultivar, vegetative growth and flowering, the significant four-way interaction of planting density, training system, cultivar and time on individual tree production was not surprising.

In all cultivars, tree production was not significantly different in the LD and MD plantings, but was generally lower in the HD planting (Figure 7). This was particularly so during the second and the third productive years, where NMBP-1243 and Keitt had significantly lower tree production in the HD planting. Tree production in the MD and HD plantings was not significantly affected by the training system in any of the three cultivars, despite marked differences in tree production. For example, in the MD planting, NMBP-1243 produced more in single leader trees than conventional trees, and in the HD planting, Keitt espalier trees produced more than conventional trees (Figure 7). For each cultivar, some combinations of planting density and training system gave higher individual tree production during the first three productive years. NMBP-1243 trees performed better under single leader training in MD planting. But for Keitt and NMBP-1243, conventionally trained trees in the HD planting were less productive than the other combinations. By contrast, Calypso tree production was not affected by the combinations of planting density and training system and appeared more adaptive to intensification. However, medium- to long-term records are necessary to conclude the effects of planting density and training system on tree production for each cultivar, since adult trees generally fill their allocated space and their production differs from that of young trees with the appearance of irregular bearing [66].

The results on tree production highlighted the productive capacity of each cultivar. Keitt was the most productive cultivar during the first three productive years, with an important first production (19.0 to 36.0 kg tree^{-1}) when compared to Calypso and especially NMBP-1243, whose first tree production was below 4.0 kg tree^{-1} on average (Figure 7). During the second and the third productive years, Keitt and Calypso tree production were similar for each training system, and significantly higher than NMBP-1243 tree production.

Orchard yield resulted from the multiplication between individual tree production and planting density. Interestingly, the four-way interaction was not significant as it was for tree production, probably because the effect of planting density on orchard yield was so important that the complex four-way interaction for tree production vanished. The effects of the combinations of planting density and training system on the 3-year average orchard yield differed among cultivars (Figure 8b). Besides the higher yields of Keitt when compared to NMBP-1243, the interaction of density × training × cultivar showed that there was a regular yield increase between the combinations for NMBP-1243, whereas yield increase was determined by planting density for Calypso and Keitt. This was probably a consequence of the low tree production in HD planting for NMBP-1243 (Figure 7). The training system had no significant effect on orchard yield in MD and HD planting, except for Keitt, whose 3-year average yield was higher for espalier trees than for conventional trees at HD.

Our results confirmed the expected positive effect of planting density on orchard yield and its changes (density $\times$ training $\times$ time interaction, Figure 8a) during the first productive years [5]. During the third productive year, the yields of HD (about 37.5 t ha^{-1}) and MD (about 17.9 t ha^{-1}) planting orchards were, on average, four and two times the yields of LD (9.0 t ha^{-1}) planting orchards, respectively. However, the number of trees in the HD planting (1250 tree ha^{-1}) was six times that at in the LD planting (208 tree ha^{-1}). Consequently, the HD planting had a negative effect on individual tree production, noticeable as early as the first productive year and shared by the three cultivars (Figure 9). This result at the orchard scale corroborated the one observed at the tree production scale (Figure 7).

The lower tree production in the HD planting could be related to differences in canopy size and/or to competition for light or between root systems. The differences in canopy size between planting densities could be compared for conventional trees only since single leader and espalier trees had specific canopy shapes. The significant differences in tree height, canopy length and width for conventional trees in LD and MD versus HD plantings were scarce and likely did not explain the lower tree production in the HD planting. It would be interesting to address this point and better estimate the potential for tree production, for example, with the canopy volume or surface, or the number of terminal growth units [66], to refine the conclusion.

The competition for light could play a role between rows for espalier trees in the HD planting since they were higher than trees of the other systems as early as the first productive year (Figure 4). But this hypothesis did not hold for conventional trees in the HD planting, whose height was similar to that of the trees in the LD and MD plantings. The 2 m distance between successive trees in the HD planting could generate competition for light and space between canopies since their length on the row was about 2 m from the first productive year (Figure 5). It could also generate competition for space, water or nutrients at the root level. The lower tree production in the HD planting was therefore more related to competitions between trees than to lower tree size. Differences in tree production caused by tree dimensions will probably prevail when the orchard ages, with the larger development of tree dimensions in the LD and MD plantings.

5. Conclusions

This study provides original and detailed results on how complex interactions between planting density, training system, cultivar and/or time affect mango tree dimensions and production during the five years after planting. Reduced vegetative growth and tree production in the HD planting suggested competition between trees from two years after planting. On a per area basis, the increased number of young trees in the HD planting more than compensated for the lower tree production. These results show that the management decisions for training and pruning the canopies significantly affect tree growth rate and production, making it difficult to draw clear technical recommendations at this stage.

These results highlight various prospects to better understand the behaviour of mango trees at higher planting densities. This experiment continues to evaluate the effects of the studied factors on the vegetative growth and fruit production of adult mango trees. Differences in canopy dimensions between planting densities and irregular bearing are two points that were not encountered with young mango trees but can affect the fruit production of adult trees. New variables and scales of study should be considered to better characterise the effects of the studied factors on tree vegetative growth, fruit production and their interactions. At the tree scale, canopy volume, canopy surface or the number of terminal growth units would better characterise the flowering and fruiting potential per tree. At the scale of the terminal growth unit, the probability of flowering, of fruiting and of vegetative growth would be meaningful variables. Specific analyses would also be necessary to investigate the hypothesis of competition between trees in HD planting.

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