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# Long-term effects of tree density and tree shape on apple orchard performance, a 20 year study—Part 1, agronomic analysis

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A B S T R A C T

While the adoption of high-density apple orchards during the last decades has resulted in a significant improvement in yield and fruit quality, there is great disparity of opinion on the optimum density or the optimum tree shape. A 2-ha replicated field trial was planted in 1997 at the New York State Agricultural Experiment Station in Geneva, New York and continued through 2016, with 4 apple cultivars ('Empire', 'Fuji', 'Gala', and 'McIntosh'), where we compared 8 tree planting densities (598, 840, 1026, 1283, 1655, 2243, 3262, and 5382 trees/ha), and two tree shapes (conic and V). At the lowest 2 densities, trees were planted on M.7 rootstock (598 trees/ha) and M.26 rootstock (840 trees/ha). At all of the higher tree densities, trees were planted on M.9. After 20 years, there was a strong negative correlation of tree planting density and trunk cross sectional area for all the cultivars and training systems, with the exception of 'McIntosh' in a V tree shape where no clear differences were observed. A different pattern for each cultivar was observed with respect to yield and planting density. High-density plantings were more appropriate for 'Fuji' and 'Gala', where conic tree shapes were better than V shapes. On the other hand, with 'Empire' and 'McIntosh' high planting density was not as beneficial. The highest yields from 'McIntosh' were realized at less than 3000 trees/ha with V tree shapes, or ~3500 trees/ha with conic tree shapes. Planting density significantly affected firmness, soluble solids, fruit color, and fruit size. Light interception for each density and shape was measured only with 'Empire'. Planting density had a strong positive effect on light interception. There were no significant differences in interception between tree shapes through the 4th leaf, however, after that more light was intercepted by the V shaped trees. Cumulative yield was a linear function of light energy intercepted by the canopy. While V tree shapes had more light interception, conic shapes seemed to have a better efficiency converting intercepted energy into yield. Planting density improved light interception, but decreased tree partitioning because of the need for more pruning leading to unbalanced trees. Tall Spindle at high planting density seemed to be the best option for cultivars with similar bearing habits such as 'Fuji' and 'Gala'.

## 1. Introduction

Increased tree planting density using dwarfing rootstocks has been the most important change in apple (*Malus* × *domestica* Borkh.) production over the last 60 years (Robinson, 2008). Apple growers around the world continue to plant high tree densities. However, there is great disparity of opinion on which density or training system is the most profitable with some growers using densities above 5000 trees/ha and some growers using densities below 500 trees/ha. The optimum planting density depends upon the interaction of numerous biological and economic variables over the life of the orchard including climate, soil resources, tree growth rate, flowering and fruiting, tree vigor, fruit price, tree price, impact of fruit quality on price, and labor costs. The evaluation of these variables to determine the optimum tree planting density has been attempted previously (Goedegebure, 1993; Robinson et al., 2007; White and Demarree, 1992). However, a limitation of these studies has been the absence of long-term field performance data on which to base the analyses. One of the objectives of this study was to develop such long-term data.

Yield from apple orchards has been related to light interception (Palmer, 2011). Tree spacing, tree shape, and tree height are primary determinants of canopy light interception. As such, these geometric variables often set the upper limit of biological yield but physiological factors can also have a large impact. The primary physiological variables in orchard systems are rootstock, canopy structure, crop load, and soil nutrient levels. These variables must be maintained for the life of the orchard as they affect the balance between vegetative growth and fruiting (Palmer, 1988). Pruning and crop load management, along

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with fertilization and irrigation, are the primary management tools used to achieve a balance between vegetative growth and cropping throughout the orchard life (Ferree and Warrington, 2003; Robinson, 2007). These management variables can be affected by planting density, tree quality, rootstock and tree training system. Training system plays a key role in the management of the tree canopy to take advantage of light interception. Higher tree planting densities can intercept high levels of light, which can translate into increased tree productivity (Lakso and Robinson, 1997; Lakso and Robinson, 2014; Palmer, 2011). However, increasing light interception does not always result in productivity gains, and in some cases it can even be detrimental (Corelli-Grappadelli and Lakso, 2007) if vegetative vigor becomes excessive thus affecting the balance between vegetative growth and fruiting. Furthermore, each cultivar has its own bearing habit, which will determine its suitability for different training systems (Lespinasse and Lauri, 1996). No system is optimum for all conditions (Barritt, 1987) and determination of the optimum system for each particular situation with consideration of cultivar, planting density, climate, and economic conditions is often done by trial and error without solid research data. Our second objective was to measure light interception and yield partitioning index over a range of planting densities to elucidate correlations with yield performance at each density.

Production of uniform high quality fruit is critical for every successful system. Fruit price is linked to fruit quality, and has the greatest effect on the potential profit of any planting system (Robinson et al., 2013). Furthermore, fruit quality can be very heterogeneous within the same tree depending upon canopy position, most likely due to different light exposure levels (Awad et al., 2001; Jajo et al., 2014; Zhang et al., 2016). Therefore, there is a need to determine the right cultivar-system-density combination that will result in the best light distribution within the canopy resulting in the highest yield with the highest quality fruit.

Increasing tree planting density has generally improved early and cumulative yields over the first 10 years (Robinson and Dominguez, 2015). Nevertheless, the law of diminishing returns (Case and Fair, 1989), which results in less gain in cumulative yield as more trees are planted per ha, means that very high tree densities are not necessarily more profitable than moderate densities. Higher density systems have greater investment costs than low density systems (Goedegebure, 1993). Still, due to higher early yield and higher cumulative yield during the first 10 years, profitability in the first decade of an orchard life is generally increased with increased tree density. Therefore, the success of any orchard system should be evaluated over the lifetime of the orchard (usually 20–25 years); however, most research studies are not conducted for such long time periods. The goal of this study was to evaluate the long term productivity, tree growth, fruit quality, and efficiency of four common apple cultivars (‘Empire’, ‘Fuji’, ‘Gala’, and ‘McIntosh’) across a wide range of planting densities to assist growers in making proper planting decisions that will provide them the best return on investment. Our third goal was to compare tree shape (conic vs. V), across a range of tree densities to determine the independent effects of shape and density.

## 2. Materials and methods

### 2.1. Trial site and design

In 1997 a 2 ha replicated field trial was planted at the New York State Agricultural Experiment Station in Geneva, New York (lat. 42.5°N, long. 77.2°W), with 4 apple cultivars (‘Empire’, ‘Fuji’, ‘Gala’, and ‘McIntosh’), where we compared 8 tree planting densities (598, 840, 1026, 1283, 1655, 2243, 3262, and 5382 trees/ha) and two tree shapes (conic and V) (Table 1). At the lowest tree density (598 trees/ha), trees were planted on M.7 rootstock while at the second lowest density (840 trees/ha) trees were planted on M.26 rootstock. All other densities were planted on M.9.T337 rootstock. The experiment was designed as a

**Table 1**
Tree densities, spacing, and rootstocks for the different planting systems evaluated at Geneva NY from 1996 to 2016.

| Tree Density (trees/ha) | Spacing (m) | Rootstock | Conic shapes | | | | V shapes | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Pruning and Training System | Initial Heading Height (cm) | Final Tree Height (m) | Max. diam. of branches allowed before branch renewal (cm) | Pruning and Training System | Initial Heading Height (cm) | Final Tree Height (m) | Max. diam. of branches allowed before branch renewal (cm) | Angle from vertical of V trellis |
| 598 | 3.3 × 5.1 | M.7 | Slender Pyramid | 120 | 5.5 | 5 | V-trellis | 60 | 2.5 | 5 | 30 |
| 840 | 2.4 × 5.0 | M.26 | Slender Pyramid | 120 | 5.0 | 5 | V-trellis | 60 | 2.5 | 5 | 30 |
| 1026 | 2.1 × 4.6 | M.9 | Vertical Axis | 120 | 4.5 | 4 | V-trellis | 60 | 2.5 | 4 | 30 |
| 1283 | 1.8 × 4.3 | M.9 | Vertical Axis | 120 | 4 | 4 | V-trellis | 60 | 2.5 | 4 | 25 |
| 1655 | 1.5 × 4.0 | M.9 | Vertical Axis | 120 | 3.75 | 4 | V-trellis | 60 | 2.5 | 4 | 20 |
| 2243 | 1.2 × 3.7 | M.9 | Slender Axis | 120 | 3.5 | 3 | V-Slender Axis | 120 | 2.75 | 3 | 20 |
| 3262 | 0.9 × 3.4 | M.9 | Tall Spindle | 120 | 3.25 | 3 | V-Tall Spindle | 120 | 2.75 | 3 | 15 |
| 5382 | 0.6 × 3.1 | M.9 | Super Spindle | 180 | 3.0 | 2 | V-Super Spindle | 180 | 2.75 | 2 | 15 |

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