A Vision for Apple Orchard Systems of the Future

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There has been a steady increase in tree planting density over the last 50 years from 40 trees/acre to in some cases more than 3,000 trees/acre. Since the beginning of this planting system revolution growers in NY State have progressively moved from multiple leader trees on seedling rootstocks at 40 trees/acre to the central leader system on semi-dwarfing rootstocks at 200 trees/acre, to the slender spindle system on fully dwarfing rootstocks at 600 trees/acre, to small central leader trees on M.9/MM.111 interstem root systems at 400 trees/acre to the vertical axis system on dwarfing rootstocks at 500 trees/acre, to the super spindle system on dwarfing rootstocks at 2,200 trees/acre to the tall spindle system at 1,000 trees/acre. In this article we would like to present a vision for the orchards of the next 20 years.

Five Important Principles of Orchard Systems

Throughout the evolution in planting density several important principles have been discovered which have guided this change.

First, studies on light interception illustrated that to achieve high mature yields orchard canopies must intercept a high proportion of available light (70-75%). Pedestrian orchards with regular tractor alleys do not intercept more than 55% of available light unless tractor alleys are very narrow (7ft.). This requires that orchards be relatively tall (10-11 feet) with our current tractors and bins.

Second, studies on light distribution have shown that thick canopies have too much heavily shaded area with poor fruit quality in those areas. Narrow canopies or planar canopies with a depth of no more than 3 feet have better light distribution. This has led the effort to narrow the canopy of modern orchards to no more than 3 feet deep.

Third, the need for high early yield to pay back the initial investment to plant the orchard has prompted significant work on improving early yield. This has led to the use of use of feathered trees, planting higher tree densities, maximizing tree growth after planting with irrigation and fertigation, minimizing pruning at planting and in the first 3 years and branch bending to induce early cropping. With the use of highly feathered trees, significant yield can be achieved in the second year after planting.

Fourth, simple and thin tree canopies are more adaptable to partial mechanization of some orchard management practices than thick, complex tree canopies.

Fifth, orchard planting density is limited by the economic law of diminishing returns. As planting density is increased the additional benefit in yield is smaller and smaller with each additional tree. At some point the cost of additional trees is greater than the gain in yield.

Economic Analysis of Orchard Systems

At the turn of the last century there was a great disparity of opinion among USA growers on which system was the most profitable with some growers using densities above 2,200 trees/acre and some growers continuing to use densities below 200 trees/acre. To help guide the planting density decision we conducted an economic analysis of profitability and costs of the most promising orchard planting systems over a wide range of densities using data from our orchard systems trials in NY State.

Five common orchard systems were evaluated for profitability in NY State in 2003 and again in 2010. They included: Slender Pyramid, Vertical Axis, Slender Axis, Tall Spindle and Super Spindle (Robinson et al., 2007). They ranged in density from 340-2,200 trees/acre which represents a broad range of tree densities. The analysis estimated Net Present Value (NPV) for each system over 20 years. The methods and results were reported previously (Robinson, et al., 2007).

Optimum Planting Density. In general our results showed that the greater the planting density, the greater the investment cost to establish the orchard. However, due to higher early yield and higher cumulative yield, profitability was generally increased with increased tree density up to a point. Nevertheless, the law of diminishing returns which results in less gain in cumulative yield as more trees are planted per ha, meant that very high tree densities were not more profitable than more moderate densities. In addition, economists suggest that risk increases with increasing level of investment, thus making the very high-density systems riskier.

When NPV of the accumulated profit over 20 years was calculated per unit land area the greatest profitability was at a tree density of 1,050 trees/acre when feathered trees were used (Figure 1). When an alternative method to evaluating profitability (NPV per unit of capital invested rather than per unit of land area) the optimum tree density was slightly lower (around 950 trees/acre).
We repeated the analysis in 2010 and used higher fruit prices and better early tree growth and yield in the first 5 years (due to advances in tree quality and better management methods after planting and NPV was significantly higher for each orchard system but the optimum planting density was 1,100 trees/acre (Figure 1).

**Effect of Tree and Fruit Price.** Fruit price had the greatest effect on the potential profit of each planting system. All systems were profitable at a fruit price of $0.30/kg ($0.14/lb.) (excluding packing, storage and marketing expenses). If fruit price was reduced to $0.25 ($0.11/lb.), none of the systems were profitable (Figure 1C). If fruit prices were very high ($0.55/kg or $0.25/lb.) such as with a new club variety the shape of the curve was asymptotic with the highest density system having the greatest profitability. A doubling of the fruit price from $0.30 to $0.55 resulted in a 9-fold increase in profitability. The high-density systems were more sensitive to price than the low-density systems. This means that under low prices they drop the most, but also under high prices they benefit the most. With low prices of $0.25/kg the optimum tree planting density was 2,450 trees/ha (1,000 trees/acre) while with moderately high fruit prices of $0.35/kg the optimum planting density was 2,800 trees/ha (1133 trees/acre). At very high fruit prices of $0.55/kg the optimum tree density was ~5,500 trees/ha (2225 trees/acre).

Tree price and trellis cost had a large influence on profitability and optimum planting density. At low tree planting densities, tree price had only a small effect on profitability while at high planting densities, tree price had a very large impact on profitability. With high tree prices, profitability of all systems was low and the optimum tree density was 2,400 trees/ha (1000 trees/acre). As tree price was reduced, profitability of each system was increased and the optimum planting density increased. With an extremely low tree price of $2.00/tree, the optimum density was above 5,500 trees/ha (2,225 trees/acre).

In general our economic study indicated an optimum tree density of 1,000-1300 trees/acre unless fruit price was very high and tree price was very low. This range of tree densities led to the development of a training system for this density we call the Tall Spindle.

**The Seven Leading Planting Systems Around the World**

The 7 leading systems in the world are: Tall Spindle, Super Spindle, Vertical or V-trellis, Solaxe, Bi-Axis and Fruiting Wall (Figure 2). All seven systems use high tree densities (900-2,200 trees/acre) and depend on early production to repay the initial investment. The Tall Spindle is the most common system in eastern North America with most growers using 1,000-1,300 trees/ha. It is simple to learn and requires moderate initial investments, has high early yield and is estimated to provide the highest profitability over 20 years. A few growers are planting Super Spindle orchards at 2,200 trees/acre but these are limited to growers who produce their own trees. The super spindle has a simplified pruning recipe and high fruit quality.

![Image of six leading orchard systems](image-url)
The Organized trellis systems (V-trellis and Vertical trellis) are common in Washington but not in the East. These two systems are designed for precision pruning where bud numbers are reduced through pruning to a pre-calculated number. In addition growers claim less sunburn with these systems. The Solaxe system is common in southern France, parts of Spain and Chile but is not adopted in other parts of the world. It uses extensive limb bending and manual bud extinction to achieve a balance of vegetative growth and cropping even when vigor is excessive. The bud extinction also helps controls biennial bearing. The bi-axis system is new to North America but has been used in Italy for about 8 years. It uses a two-stem tree to achieve a very high number of leaders per acre (1,800) with only a moderate number of trees per acre (900). It also distributes tree vigor to two leaders giving more moderate growth in each leader. The system has its greatest potential when tree vigor is difficult to manage with traditional Tall Spindle training. This system is well adapted to mechanical pruning. In NY we have one 6-year-old trial with Red Delicious using a multiple leader system that looks promising. The last system is the “Mur Frutiere” or Fruiting Wall from southern France, which has some adoption in Italy, Germany, Belgium and Spain. It uses mechanized sidewall shearing during the early summer to reduce pruning costs and achieve high yields and good fruit quality.

It is interesting that some successful apple growers manage apple trees with complete precision of bud load as with the organized trellis systems while other successful apple growers use a completely mechanized system with no precision of bud management. This indicates that there are many ways to “skin a cat”.

The Tall Spindle System

Of the seven leading planting systems in the world we believe the Tall Spindle system has the greatest potential to incorporates all five of the important principles of orchard systems. It is an amalgamation of the slender spindle, the vertical axis, the super spindle and the Solaxe systems (Robinson et al., 2006). This system utilizes the concept of high tree densities from the slender spindle system but utilizes lower planting densities than the Super Spindle (~1,000-1,300 trees/acre). The system uses tall trees similar to the Vertical Axis but very narrow canopies like the Super Spindle. It also uses highly feathered trees (10-15 feathers) and pendant limb angles like the Solaxe to induce cropping and reduce branch growth and vigor. The system also utilizes minimal pruning at planting and during the first 3 years. In contrast to the slender spindle system, which includes cutting of the central leader which results in a vigorous frame, the Tall Spindle utilizes no pruning of the leader. Without pruning of the leader and with feathers starting at 80 cm above the soil, the tall spindle tree can be allowed to crop in the second year, which gives natural bending of lateral branches, which keeps them weak. At maturity the Tall Spindle canopy has a dominant central trunk and no permanent scaffold branches. Limb renewal pruning is utilized to remove and renew branches as they get too large (>3/4 inch or >2cm diameter).

Tree density with Tall Spindle orchards can vary from a high of 1,452 trees/acre (3 X 10 feet) to a low of 908 trees/acre (4 X 12 feet). The proper density considers the vigor of the variety, vigor of the rootstock, and soil strength. For weak and moderate growing cultivars such as Honeycrisp, Delicious, Braeburn, Empire, Jonamac, Macoun, Idared, Gala, NY674, and Golden Delicious we suggest an in-row spacing of 3 feet (Figure 2A) For vigorous varieties such as McIntosh, Spartan, Fuji, Jonagold, Mutsu, etc. and tip bearing varieties such as, Cortland, Rome Beauty, Granny Smith and Gingergold we suggest an in-row spacing of 3.3-4 feet. Between-row spacing should be 11-12 feet on level ground and 12-13 ft. on slopes.

Dwarfing rootstocks such M.9, B.9 or the fire blight resistant dwarf rootstocks from Geneva” (G.11, G.41 and G.935) have been used successfully in Tall Spindle plantings. The weaker clones (M.9NAKBT337, M.9Flueren56, B.9 G.11 and G.41) are especially useful with vigorous scion varieties on virgin soil. The more vigorous clones (M.9Pajam 2, M.9Nic29, M.9EMLA, and G.935) are much better when orchards are planted on replanted soil or when weak scion cultivars are used.

An essential component of the Tall Spindle system is a highly branched (feathered) nursery trees. The tall spindle system depends on significant 2nd and 3rd year yield, for the economic success of
the system. If growers use whips or small caliper trees which do not produce significant quantities of fruit until year 4 or 5, often the carrying costs from the extremely high investment of the tall spindle orchard overwhelms the potential returns and negates the benefit of the high tree density on profitability. We recommend that the caliper of trees used in tall spindle plantings be a minimum of 5/8 inch and that they have 10-15 well positioned feathers with a maximum length of 1 foot and starting at a minimum height to 28 inches on the tree (Figure 2A). Generally nursery trees in North America have not had this number of feathers until recently. Many nursery trees have 3-5 long feathers instead of 10 short feathers (Fig 2B). The tree with fewer long feathers requires more branch management than the tree with more short feathers.

One of the most significant differences between the Tall Spindle and the more traditional Vertical Axis and Slender Spindle systems is that the tall spindle tree typically has no permanent lower tier of branches. With the Tall Spindle all of the feathers are tied or weighted below the horizontal at planting to induce cropping and to prevent them from developing into substantial lower scaffolds (Fig 2B). The pendant position results in a weak fruiting branch instead of a scaffold branch. With the Vertical Axis and Slender Spindle systems the feathers are tied down a little above horizontal, which allows them to grow into scaffolds over the first 4 year. Growers who attempt to plant feathered trees at the Tall Spindle spacing but do not tie the feathers down often end up with limbs in the lower part of the tree that are too strong which requires severe limb removal pruning at an early age which invigorates the tree and makes long term canopy containment problematic. This simple change in feather management allows for long-term cropping of many feathers and little invasive pruning for the first 5-8 years at the very close spacing of the Tall Spindle system.

After the initial tying down of feathers at planting, new lateral branches that arise along the leader do not need to be tied down. In most climates, moderate tree vigor is obtained and lateral shoots arising along the leader often bend below horizontal with crop load in the third year. This creates a natural balance between vigor and cropping without additional limb positioning. However, in vigorous climates or where winter chilling is insufficient, often limbs become too large before they set sufficient crop loads to bend the branches down. In these climates, tying down of all vigorous limbs must be done annually for the first 3-5 years until the tree settles down and begins to crop heavily. However, in most traditional apple growing areas, growers often invest too much money in limb tying which should be limited to only the feathers at planting. Thereafter, the precocity of the rootstock induces heavy cropping and a natural balance is established.

With precocious dwarfing rootstocks, young apple trees can often overset in the 2nd or 3rd year resulting in biennial bearing as early as the 4th year. This then results in increased vigor in the 4th year just when the trees have filled their allotted space and when reduced vigor is needed. Varieties differ in their biennial bearing tendency and this must be incorporated into the crop loads allowed on young trees. For annual cropping varieties like Gala, we recommend crop loads of 20-40 apples/tree in the second year, 60-100 apples/tree in the third year. For slow growing and biennial bearing varieties like Honeycrisp crop loads should be half that used with Gala.

Good light distribution and good fruit quality can be maintained as trees age if the top of the Tall Spindle tree is kept more narrow than the bottom of the tree and if there is a good balance between vegetative growth and cropping. For the Tall Spindle system, maintaining a conic shape as the ages is critical to maintaining good light exposure, in the bottom of the tree. In our experience, the best way to maintain good light distribution within the canopy as the tree ages is to remove whole limbs in the top of the tree once they grow too long rather than shortening back permanent scaffold branches in the tops of trees. A successful approach to managing the tops of trees has been to annually remove 1-2 upper branches completely. To assure the development of a replacement branch, the large branch should be removed with an angled or beveled cut so that a small stub of the lower portion of the branch remains. From this stub a flat weak replacement branch often grows. If these are left un-headed they will naturally bend down with crop.

A key feature of the Tall Spindle system is a simple pruning system that is less expensive than traditional “mold and hold” pruning or the complex pruning spur extinction and centrifugal pruning of the Solaxe. In addition, the cost of the simple pruning of the Tall Spindle can be further reduced by partial mechanization with orchard platforms. With the Tall Spindle, we have measured savings of 30% in dormant pruning costs with self-steering pruning platforms compared to traditional pruning with ladders (Miranda-Sazo et al. 2010). Motorized platforms can also reduce harvest, hand thinning and tree training costs.

**Efforts to Reduce Costs Per Unit of Production**

**Less Expensive Planting Systems.** High-density systems are expensive to establish. The greatest initial cost is for the trees. If the cost of trees could be reduced without reducing early yield then profitability could be increased. Several recent efforts have attempted to examine the impact of utilizing less expensive trees. Some growers have begun growing their own trees to reduce tree costs. This usually results in medium size un-branched trees instead of large caliper highly feathered trees. A few growers have planted fall budded rootstocks (sleeping eye trees) and others have planted spring grafted rootstocks (bench grafts). The initial cost of such orchards is substantially less than using feathered trees; however, early yields are also delayed by one year. The economic value of such a strategy has been studied in only one replicated experiment (Robinson and Hoying, 2005). In our study, tree quality at planting had a significant impact on profitability. Although large caliper feathered trees produced more fruit in the first few years, the yield benefit was somewhat offset by higher initial tree price. The more expensive large-caliper, feathered trees were more profitable when planted at low to medium-high densities while sleeping eye or 1 year grafts were more profitable at the very high densities. At the optimum planting density of 1,000 trees/acre (from our economic study), feathered trees were the most profitable while at densities above 2,000 trees/acre the less expensive sleeping eye or 1 year grafted trees were the most profitable.

**Mechanization.** In addition to improving yield and thereby reducing production costs per unit of production through high-density orchard systems, apple growers have begun an effort to reduce costs through partial mechanization of orchard tasks including platforms for dormant pruning, and hand thinning and summer shearing for summer pruning (Table 1).

Motorized platforms are now common in NY and other eastern states. Significant acreage is currently managed with self-steering motorized platforms for dormant pruning, hand thinning, trellis construction and tree training. Almost none are being used for harvest but we expect that over the next 5 years many growers will begin to use one of the various harvest assist platform. The
Table 1. Potential labor savings with a Tall Spindle orchard mechanized with platforms for pruning, hand thinning, tree training and hanging pheromones, and with summer hedging and a harvest assist machine.

<table>
<thead>
<tr>
<th>Labor Inputs</th>
<th>Traditional Vertical Axis Trees (1000 bu/ac with ladders)</th>
<th>Tall Spindle Trees (1500 bu/ac with platforms)</th>
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</thead>
<tbody>
<tr>
<td>Dormant Pruning</td>
<td>60 hours/acre</td>
<td>30 hours/acre</td>
</tr>
<tr>
<td>Tree Training</td>
<td>20 hours/acre</td>
<td>10 hours/acre</td>
</tr>
<tr>
<td>Hand Thinning</td>
<td>80 hours/acre</td>
<td>30 hours/acre</td>
</tr>
<tr>
<td>Hanging Pheromones</td>
<td>40 hours/acre</td>
<td>20 hours/acre</td>
</tr>
<tr>
<td>Summer Pruning</td>
<td>60 hours/acre</td>
<td>1 hour/acre</td>
</tr>
<tr>
<td><strong>Total Pre-harvest Labor</strong></td>
<td><strong>260 hours/acre</strong></td>
<td><strong>91 hours/acre</strong></td>
</tr>
<tr>
<td>Harvest</td>
<td>100 hours/acre (4 bins/person/day)</td>
<td>75 hours/acre (8 bins/person/day)</td>
</tr>
<tr>
<td><strong>Total Annual Labor</strong></td>
<td><strong>360 hours/acre</strong></td>
<td><strong>166 hours/acre</strong></td>
</tr>
</tbody>
</table>

We see little possibility of harvest mechanization with robotic machines. Although considerable money has been spent in the last 4 years on this effort it will require many more years to build such a machine due to the extreme complexity of identifying the fruit location, detaching the fruit without bruising, and transporting the fruit to the bin without bruising. If such a machine is ever developed it will likely be too expensive and too slow with little or no gain in picking efficiency. We predict the cost/benefit ratio will be negative which will likely raise the cost to harvest a bushel to harvest apples with a robotic machine. We see much greater possibilities for harvest assist machines such as the Wafler harvest platform (see companion article in this issue).

Another possibility is the use of robots to prune apple trees. This will require simple, single dimensional trees with no permanent branches such as the Tall Spindle the super spindle or the Fruiting Wall. It will also require machine vision to locate branches and map a pruning path and simple pruning rules. However, even if the feasibility of the robotic pruner is good, the economics of the idea may not be favorable. Just as with robotic harvest machines, the robotic pruning machine may be too expensive and too slow with little or no gain in pruning efficiency compared to human pruners on the self-steering motorized platforms and simple trees like the Tall Spindle. The cost/benefit ratio of a robotic pruning machine will have to be analyzed after the machine is built but it may well be negative which would raise the cost of pruning with a robotic machine.

### Planting Orchards for the Future

The planting of a new orchard is a 20-25 year commitment. Before planting a grower should consider the possible changes in orchard management that will occur in the next 25 years and try to plant the new orchard so he can benefit from advances in orchard management that are likely to occur. The 5 basic principles or orchard design outlined above (1. high light interception, 2. good light distribution throughout the canopy, 3. high early yields, 4. simple canopies are more adaptable to partial mechanization, and 5. planting density is governed by the law of diminishing returns) will be a part of any future orchard system. Our analysis of future orchards gives the following conclusions:

1. It is likely that the orchard systems of the future will be tall (10-11 feet) due to the need of intercepting 70-75% of available light. Shorter tree height are possible with very narrow rows but that will require a change in the tractor, spraying and bin handling system. Narrow row pedestrian orchards were evaluated in the mid 1980’s in the Netherlands but were not adopted due to the need for every row spraying. However, it is possible to imagine a future orchard planted with only 5-6 feet between rows (just a walking path) and with a 6 foot tall trees trained in a very narrow fruiting wall with the spraying done by a fixed over the row system. Pruning and harvesting could be done by over the row machines and bin handling done with over the row bin trailers. Although this idea is intriguing it is unlikely to occur due to little gains in yield or labor efficiency or profitability.

2. It is likely that orchard systems of the future will have narrow simple canopies no wider than 4-6 feet due to the need to have good light distribution in all regions of the canopy. In addition such narrow canopies will be more adaptable to machine pruning with shearing machines and will be easier to harvest with simple harvest aids.

3. It is likely that future orchards will continue to utilize highly branched trees for high early yields. The only exception to this rule will be those growers who choose to plant very high tree densities (>1,500 trees/acre) where the cost of feathered trees is too high and the value of feathers is less due to very small space between trees. However in our opinion such high densities will offer little additional profitability and little additional efficiency in labor or fruit quality.

4. Simple canopies will offer significant benefits in mechanization with simple platforms for pruning, thinning and harvesting. It is unlikely that complete mechanization will occur in either pruning or harvest but we believe low cost platforms for labor positioning will become the standard for both pruning and harvest. It is also likely that mechanization of summer pruning with shearing machine will become common but remedial hand pruning will be required every 2nd or 3rd year. We expect that harvest assist machines will become common but will be best adapted to narrow thin canopies.
5. It is likely that the optimum planting density will remain close to 1,000 trees/acre. As growers become more adept at managing this density they will likely plant slightly closer with densities close to 1,300 trees/acre. If they adopt summer shearing to reduce cost and to maintain a narrow canopy wall then they will slowly move from 12 feet between rows to 11, 10 or 9 feet between rows.

Conclusions
The change in planting systems over the last 50 years has been dramatic. As we look to the future the current best system, the Tall Spindle, is likely to continue to be the best system with small modifications of a narrower canopy maintained by mechanical side wall shearing to reduce labor costs and to improve fruit quality. It is likely that narrow canopy fruiting wall type orchards will be harvested and pruned with harvest assist platforms. We expect such orchards to have very high yields (1500 bu/acre) with uniformly high fruit quality. We believe that such future orchards can be managed with significantly less total annual labor hours.

Literature Cited

Terence Robinson is a research and extension professor at Cornell’s Geneva Experiment Station who leads Cornell’s program in high-density orchard systems and plant growth regulators. Steve Hoying is a senior extension associate who is located at Cornell’s Hudson Valley Lab who specializes in orchard management. Mario Miranda Sazo is an Extension Associate who specializes in orchard management with the Lake Ontario Fruit Program of Cornell Cooperative Extension. Alison DeMarree is an Extension Associate who specializes in farm business management and economics with the Lake Ontario Fruit Program of Cornell Cooperative Extension. Leonel Dominguez is a graduate student and research support specialist who works with Dr. Robinson.