# The Productivity and Performance of Apple Orchard Systems in Australia

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> ***The lifetime success or failure of a planting system can be predicted as early as the third leaf, based on midseason measures of light interception and leaf area.***

Apple orchard light interception and distribution are the keys to high yields and fruit quality. Apple yields increase with increasing light interception until a point is reached where the canopy is too dense and/or excessive tree spread and height lead to severe shading effects, with consequent declines in productivity (Jackson, 1980a). It is well documented that internal tree shading can reduce apple yield, fruit size, color and total soluble solids (TSS) (Doud and Ferree, 1980).

As a small apple producer by world standards, Australia must supply high quality apples produced from efficient growing systems. Australian apple production occurs between latitudes 28°S and 44°S, with the bulk of the crop produced between 33°S and 38°S. Although the sunlight intensities of Australian apple production regions are high relative to other apple producing regions throughout the world (Jackson, 1997), many commercial orchards are not attaining their yield and fruit quality potential.

Low productivity in apple orchards can be broadly attributed to either 1) insufficient tree size and canopy volume or 2) excessive tree vigor and internal shading. The aim in the design, planting and management of any orchard system is to create and maintain a desirable tree form (height, shape, spread, leaf area) that intercepts as much sunlight as possible while ensuring that light reaches all parts of the canopy.

Over the past 4 years, the productivity and performance of apple orchard systems throughout Australia have been measured and compared in terms of light interception, leaf area, tree dimensions, yield and fruit quality. The objective was to determine the light interception, leaf area and tree conformations (height, spread) required for high apple orchard productivity, to measure how closely current commercial orchard systems match these levels, and to develop a "vision" for ideal orchard design appropriate to Australia.

## METHODS

### Flatbed Solarimeters

Solid models designed to represent a range of orchard systems were placed on a flatbed solarimeter in the field and used to determine the effect of tree arrangement, height, spread, shape, planting density and row orientation on orchard light interception. These measurements were taken in midseason (January) and in March in all major apple producing regions throughout Australia. The flatbed solarimeter (described by Middleton, 1990; Middleton and McWaters, 1997) measurements define the maximum potential light interception (Fmax) by a particular orchard system, assuming the trees are "solid" and nontransmitting.

The theory of the approach is described in detail by Jackson (1980b), and based on the simple model of Jackson and Palmer (1979), where light transmission (T) through a discontinuous canopy such as a tree fruit orchard can be considered in terms of two discrete components such that:

$$T = T_f + T_c$$

where T is the total light transmitted to the orchard floor; $T_f$ is the light which misses the trees completely and would reach the ground even if the trees were "solid;" and $T_c$ is the light which passes through the tree canopy. $T_f$ is dependent on canopy geometry (form) and $T_c$ is dependent on leaf area and density.

### Light Measurements Within Apple Tree Canopies

Sunlight levels, yield, fruit quality and leaf area were measured within apple trees of a range of varieties across Australia to determine the critical light levels required for high yields and fruit quality and the leaf area distribution and tree conformations that ensure most of the canopy receives these light levels. Cosine-corrected silicon cell light meters were positioned in different parts of the tree canopy and light readings logged at 6-minute intervals between sunrise and sunset.

### Light Interception of Apple Orchard Systems Throughout Australia

The light interception, leaf area, yield and fruit quality of 120 apple orchard systems were measured on research stations and commercial apple orchards in five states of Australia (Qld, NSW, Tas, SA and WA). All significant apple orchard system rootstock x planting density trials in Australia and a wide range of apple varieties, rootstocks, tree ages, tree vigors and planting densities were included in the study.

Tree densities varied from traditional wide-spaced vase trees (270 trees/ha; 109 trees/acre) to ultra-high density V trellis double-row systems of 10,000 trees/ha (4047 trees/acre). Varieties included Royal Gala, Hi Early Red Delicious, Red Fuji, Pink Lady and Sundowner, and rootstocks included Northern Spy, MM.104, MM.106, M.26, M.9 and Ottawa 3.

Light interception was measured with an AccuPAR linear ceptometer (model SF-80, Decagon Devices, Pullman, Washington, USA), using a procedure as described by Wünsche et al. (1995). Light interception was measured on at least two occasions during the season (more frequently in Queensland and New South Wales):

- summer (Dec./Feb.), when leaf canopy development was complete and the sun at its highest seasonal altitude and azimuth.
- harvest (March/April/May), when solar angles were lower toward the end of the season and when yield and fruit quality measures were also made.

Diurnal light interception was calculated from ceptometer measurements taken a minimum of 5 times throughout the day (at 1.5- or 2-hour intervals) to fully encompass diurnal changes in solar altitude, azimuth and cast shadow length. Depending on the orchard system design, up to 120 separate ceptometer readings were required at each measurement time to adequately sample the variable light environment beneath the trees and into the alleyway.

Orchard system leaf area index (LAI), a measure of leaf density and therefore internal tree shading, was calculated from leaf counts and average individual leaf areas ($cm^2$). All of the leaves on three trees per plot were counted. Spur leaves and shoot leaves were counted separately. Individual leaf areas were measured nondestructively in the field with a perspex grid as described by Freeman and Bolas (1956), using a random sample of up to 50 spurs per tree for spur leaves, and 15 extension shoots per tree for shoot leaves. LAI (leaf area index) was calculated as $m^2$ leaf per tree/$m^2$ orchard floor surface area.

The individual leaf areas estimated from the grid were highly correlated ($r^2$ >0.90) with measures made in the laboratory with a Licor LI-3000 leaf area meter (Licor Instrument Co., Lincoln, Nebraska, USA), for all four varieties tested (Galaxy, Red Fuji, Pink Lady and Sundowner).

The color of red apple varieties was assessed visually on a scale of 1 to 5. Color ratings of 1 (very poor) or 2 (poor) were used for fruit of unacceptable, substandard color; 3 for adequately colored fruit; and 4 (good) or 5 (excellent) for apples with superior, premium color. Sunburn and russet were visually assessed on all harvested fruit, using a scale of 0 (nil), 1 (slight) or 2 (severe).

## RESULTS

Flatbed solarimeter measurements in the apple producing regions of all Australian states (28°37´S to 43°02´S) show that in midseason (January) when the trees are at full leaf, north/south rows always intercept more sunlight than comparable east/west rows (Table 1). As solar altitude and azimuth decline, the light interception by east/west rows increases toward the end of the season and at harvest (late March/April) is greater than comparable north/south row orientations (Table 1). This is too late to benefit fruit bud initiation, seasonal photosynthesis and fruitlet development.

The light distribution within east/west rows also can be poor and is dependent on tree vigor. The sunlight that is intercepted by east/west rows is largely on the exposed northern side (in the northern hemisphere it would be the south side of east/west rows), with the southern side remaining relatively shaded. If trees are too tall, alleyways too narrow or the leaf canopy too dense, the deficiencies of east/west rows become more marked. Here, fruit on the upper northern side of the trees is susceptible to sunburn, while low yields of poor size and quality are produced on the southern side.

Orchard light interception is increased with taller trees and narrower alleyways, but a point will be reached where light distribution in the canopy and, hence, yield and apple quality are adversely affected. Increasing tree height from 2.8 to 4.3 meters increased potential light interception (Fmax) by just 6 to 10% (Table 1). Although this can lead to small yield improvements, any gain is often at the expense of yield and fruit quality low in the canopy. With insufficient light, the crop closer to the ground declines and is of poor quality. It is not economically desirable to concentrate the cropping zone toward the tops of tall trees. Reducing alley width from 6 meters to 4 meters is a far more efficient way to increase Fmax, with a 14 to 21% increase in light interception (Table 1).

Even in well-illuminated trees where considerable light penetrates the canopy and reaches the orchard floor, light measurements show that some parts of the tree receive less than 10% of incident sunlight levels throughout the day. At such low light intensities, fruit set and quality are poor and trees require restructuring to open up the canopy in those regions.

Maintaining a narrow canopy depth in all the directions from which sunlight may be coming is a sound principle that is a feature of many apple orchard designs, including Tatura trellis, V trellis and Spindlebush systems. The more leaves there are above or outside a certain point in the canopy, the less likely it is for light to reach there. Hence, in productive orchards all fruit-bearing regions are never far from an outside surface of the tree. Trees of rectangular cross-section can intercept more light (Table 1), however, if the canopy is too dense this will be at the expense of light penetration, yield and fruit quality lower in the tree.

### TABLE 1

The % light interception (Fmax) in January (midseason) and March (harvest) by solid nontransmitting trees of 10 apple orchard systems at Stanthorpe, Queensland (28°37´S).

| System[Z] | Row orientation | Alley width (m) | Tree height (m) | January Fmax (%) | March Fmax (%) |
|---|---|---|---|---|---|
| 1 | N/S rows | 6 | 2.8 | 63 | 61 |
| 2 | N/S rows | 4 | 2.8 | 81 | 81 |
| 3 | N/S rows | 4 | 4.3 | 87 | 86 |
| 4 | N/S rows | 6 | 4.3 | 73 | 70 |
| 5 | E/W rows | 6 | 2.8 | 47 | 66 |
| 6 | E/W rows | 4 | 2.8 | 66 | 88 |
| 7 | E/W rows | 4 | 4.3 | 73 | 93 |
| 8 | E/W rows | 6 | 4.3 | 52 | 78 |
| 9 | N/S rows | 6 | 2.8 | 41 | 40 |
| 10 | N/S rows | 4 | 2.8 | 57 | 57 |

[Z]Systems 1-8: Rectangular cross-section (vertical side, continuous hedgerow canopy at all heights). Systems 9-10: Angled cross-section (45° sides, pyramidal shape, well-defined central leader with gaps between trees). The tree spread of all systems was assumed to be 1.25 m into each adjacent alleyway.

### TABLE 2

The light interception and yield of Pink Lady trees (third leaf) on MM.106/M.9 interstem at Grove, Tasmania (43°02´S).

| System (in-row spacing in m) | Tree density (trees/ha) | Light interception (%) | Yield (kg/tree) | Yield (t/ha) | Color (% poor) |
|---|---|---|---|---|---|
| 0.5 m single | 5000 | 36 | 4.8 | 24.2 | 8 |
| 1.0 m single | 2500 | 36 | 11.7 | 29.2 | 5 |
| 1.5 m single | 1666 | 32 | 10.8 | 18.0 | 0 |
| 0.5 m V | 10000 | 59 | 4.4 | 43.5 | 40 |
| 1.0 m V | 5000 | 53 | 8.6 | 43.0 | 40 |
| 1.5 m V | 3333 | 43 | 11.0 | 36.7 | 28 |

## LIGHT INTERCEPTION AND PRODUCTIVITY OF ORCHARD SYSTEMS THROUGHOUT AUSTRALIA

### Tasmania

A high density planting (HDP) systems trial at Grove, Tasmania, showed that it is possible to achieve close to 60% light interception for Pink Lady trees in their third leaf (Table 2). Double-row V-trellis systems facilitate high early light interception and high early yields as a result of 1) the orientation of the entire tree at an angle (15° or similar from the vertical) to efficiently capture sunlight and 2) the high planting densities used. The arrangement of trees in the V trellis at a 15° angle from the vertical permits higher interception of light than with equivalent upright trees. At a density of 5000 trees/ha (2024 trees/acre), trees planted as a 4 m x 1 m (13.1 ft x 3.3 ft) double-row V trellis intercepted more light and produced higher yields than if the trees were planted at the same density in single rows of 4 m x 0.5 m (13.1 ft x 1.6 ft) spacing (Table 2).

As the Pink Lady trees (Table 2) continue to age and grow and the initial advantage of the higher density systems in achieving high early light interception and yields begins to wane, it is likely that tree densities above 2500 to 3333 trees/ha (1012 to 1349 trees/acre) in this trial will lose their early comparative advantage as a result of vigor-induced declines in fruit quality.

As early as their third leaf the Pink Lady 0.5 m (1.6 ft) and 1.0 m (3.3 ft) double-row V-trellis systems (Table 2) had a LAI >2.0. The high vigor of Pink Lady trees generally meant that a small level of leaf stripping was already necessary in year 2 and quite significant summer pruning required in year 3 to open up the canopy a few weeks before harvest to facilitate fruit color development. All Pink Lady trees were summer pruned in year 3, with up to 30% of the leaf area removed.

The color development on Pink Lady fruit was affected by planting density, with a higher proportion of poorly colored apples produced as tree density increased (Table 2). The leaf area index (LAI, leaf density) of the Pink Lady 0.5 m and 1.0 m double-row trellis systems was already high enough in their third leaf that 40% of the apples produced were of poor color.

All trees were grown in north/south rows, and on the V-trellis systems Pink Lady fruit color was far better on fruit facing the west. Apples on the eastern side of the V-trellis were of poorer color, whether located on the underside of the eastern arm or on the more exposed internal eastern side of the western arm. On the eastern side of the V trellis fruit facing north developed blush on their north facing surfaces, whereas fruit facing south developed very little color at all. Sunburn levels were low (both single rows and V trellis), but there were noticeably more sunburnt fruits on the western facing sides of all trees. Fruit color and sunburn problems would be exacerbated at such high densities if the rows were oriented east/west.

For both Pink Lady and Sundowner there was no yield advantage in doubling the tree density of single rows from 2500 to 5000 trees/ha or of V trellis double rows from 5000 to 10,000 trees/ha. As tree density increases to such high levels, the management of varieties such as Pink Lady becomes critical to ensure high packouts of quality fruit.

### South Australia

The light interception and leaf area index (LAI) of a range of orchard systems at Lenswood, SA, is shown in Table 3. The light interception of the east-west rows increased between mid-summer and later in the season, however in April (Red Fuji harvest) the vigorous 5.5 meter high trees on MM.106 intercepted only 2% more light than MM.111 trees that were almost 2 meters shorter. The effect of the additional 1.9 meters of tree height was merely to double the LAI from 1.65 to 3.34 and reduce the volume of well-illuminated canopy through internal shading effects. Although an annual yield of 47 tonnes/hectare was produced by the Red Fuji/MM.106 trees, poor light distribution due to excessive vigor meant that only 30 tonnes/ha of fruit was of acceptable quality.

With a leaf area index (LAI) of 0.88 the Red Fuji trees on M.26 were of insufficient vigor for high orchard productivity. Although intercepting 47% of incident sunlight (Table 3), the Red Fuji/M.26 trees were spaced too far apart for the low vigor of the rootstock, and large gaps occurred between trees. With a LAI of 2.11 in their 6th leaf, the Pink Lady/M.26 trees in north/south rows (Table 3) are close to the "ideal" tree conformation. At a 2.8 meter tree height and with angled sides and a well-defined central leader, this tree conformation was consistently among the most productive at a range of sites across Australia.

Although north/south row orientation is preferable at the latitudes of Australian apple producing regions, the results for the east/west rows in SA are relevant. The very steep topography of the Adelaide Hills apple growing region means that by necessity many of the orchards must be planted in east/west rows or at orientations that are closer to east/west than the preferred north/south.

The light interception and leaf area index (LAI) of trees planted in east/west rows at 2000 trees/ha (809 trees/acre) (Table 4) again highlight the excessive vigor of MM.106 (LAI of 3.78) at Lenswood, SA, and the poor canopy development of trees on M.9. With LAI in the range of 1.7 to 2.2, the trees on Ottawa 3 rootstock are expected to continue to perform well in this trial. The midseason light interception of the trees on Ottawa 3 would also be higher and closer to optimal if the rows were oriented north/south instead of east/west. This trial is discussed in more detail by James and Middleton (2001).

### Western Australia

The light interception and productivity of a range of systems on commercial apple orchards in Western Australia are shown in Tables 5 and 6. The 5.5 meter tall vase Sundowner trees planted at a traditional 6m x 6m spacing (270 trees/ha; 109 trees/acre) intercepted just 43% of incident light despite their huge size and leaf area of 57m$^2$/tree. This level of light interception is comparable to the 44% intercepted by the high density Pink Lady MM.106 and Pink Lady V-trellis systems in only their third leaf (Table 5). The low diurnal light interception of the wide-spaced vase trees is also coupled with poor light distribution. A dense leaf canopy that permits virtually no light penetration to the orchard floor is surrounded by wide tracts of orchard space that intercept no sunlight at all.

The rootstock influence on tree vigor and light interception is evident for the single rows planted at 800 trees/ha, with Sundowner trees on MM.106 having 25% lower leaf area and intercepting 9% less sunlight than the Sundowner on MM.104 rootstock at the same density. The light interception (60%) and yields of the Sundowner on MM.104 (800 trees/ha) are close to optimum for high productivity. By contrast, the leaf area index (LAI) of the MM.106 trees should be higher to capture more of the sunlight that is penetrating to the orchard floor and thereby lift diurnal midseason light interception above 51%.

The Pink Lady V trellis system illustrates the ability of high density plantings to intercept high levels of sunlight early in the life of the orchard, utilizing trees of small leaf area (3.0 m$^2$ per tree). At a density of 4400 trees/ha the in-

### TABLE 3

**The light interception (April), leaf area index (LAI) and productivity of apple orchard systems for Red Fuji (7th leaf) and Pink Lady at Lenswood, South Australia.**

| System | Light interception (%) | Tree height (m) | LAI (leaf m$^2$/tree m$^2$) | Yield (t/ha) | |
|---|---|---|---|---|---|
| East/west rows | | | | | |
| R. Fuji/MM.106 | 70 | 5.5 | 3.34 | 47 | (60%)$^Z$ |
| R. Fuji/MM.111 | 68 | 3.6 | 1.65 | 29 | (78%) |
| R. Fuji/M.26 | 47 | 3.0 | 0.88 | 28 | (84%) |
| North/south rows | | | | | |
| Pink Lady/M.26 | 49 (4th leaf) | 2.8 | 1.50 | 37 | (95%) |
| | 59 (6th leaf) | 3.0 | 2.11 | 73 | |

$^Z$Volume of well-illuminated canopy: the canopy volume in which >75% of fruit were of class I packout.

### TABLE 4

**The midseason light interception and leaf area index (LAI) of Galaxy, Pink Lady and Sundowner trees in their fifth leaf and planted at 2000 trees/ha at Lenswood, South Australia (James and Middleton, 2001).**

| Cultivar | Rootstock | Light interception (%) | Leaf area index, LAI (leaf m$^2$/tree m$^2$) |
|---|---|---|---|
| Galaxy | Ottawa.3 | 32 | 1.71 |
| | MM.106 | 58 | 3.78 |
| Pink Lady | M.9 | 43 | 1.52 |
| | Ottawa.3 | 36 | 1.67 |
| | M.26 | 54 | 2.88 |
| Sundowner | M.9 (3rd leaf) | 10 | 0.48 |
| | Ottawa.3 | 36 | 2.16 |
| | M.26 | 29 | 2.02 |
| | M.7 | 37 | 2.20 |

### TABLE 5

**The midseason light interception and leaf area of commercial orchard systems in Western Australia (Feb 2000).**

| Sytstem | Rootstock | Tree density (trees/ha) | Light interception (%) | Leaf area (m$^2$/tree) | Leaf area Index (LAI, leaf m$^2$/tree m$^2$) |
|---|---|---|---|---|---|
| Sundowner (vase) | N. Spy | 270 | 43 | 57.1 | 1.58 |
| Sundowner | MM.104 | 800 | 60 | 32.1 | 2.56 |
| Sundowner | MM.106 | 800 | 51 | 24.2 | 1.93 |
| Sundowner (3rd leaf) | M.26 | 3080 | 34 | 3.6 | 1.11 |
| Pink Lady | MM.106 | 1000 | 64 | 16.6 | 1.66 |
| Pink Lady (3rd leaf) | MM.106 | 2222 | 44 | 7.4 | 1.64 |
| Pink Lady V trellis (3rd leaf) | | 4400 | 44 | 3.0 | 1.33 |

dividual space allotted to each tree is small, and the system can be cropped early. The subsequent success of such intensive systems relies on the ability to control tree vigor as the trees age, and the correct choice of rootstock appropriate to the planting density and training system used is a major key to the system's ultimate success or failure.

It should be noted in Table 5 that the Pink Lady/MM.106 trees (1000 trees/ha) are able to intercept similar levels of light to the Sundowner/MM.104 trees (800 trees/ha) but with only half the leaf area per tree and 65% of the orchard leaf area index of the Sundowner trees. This suggests a better leaf distribution within the Pink Lady trees that is more efficiently able to intercept sunlight with less likelihood of deleterious internal shading effects on fruit quality.

The Sundowner/MM.104 trees planted at 800 trees/ha were the most productive in Western Australia, with high yields, minimal biennial bearing (yields of 80 tonnes/ha for 3 consecutive seasons) and excellently colored fruit of good size. High fruit quality was ensured by summer pruning and close attention to tree structure. No branches were allowed to develop off the main leader for a distance of 1.2 m (3.9 ft) between the first and second tiers, thereby facilitating good light penetration to the lower, high-yielding regions of the tree canopy.

Apple production in Western Australia occurs in regions characterized by hot, dry summers. The high light intensities (2100μmol/m$^2$/sec) coupled with high temperatures means that fruit are especially prone to sunburn through exposure to radiant heat. The sunburn levels in Table 6 are typical of what can be expected, and tree structure needs to minimize fruit exposure to direct sunlight while ensuring exposure of a high proportion of the canopy to adequate light for high productivity.

The success of a commercial block of Pink Lady trees on MM.106 rootstock planted in north/south rows at a density of 2222 trees/ha (3.6 m x 1.25 m; 11.8 ft x 4.1 ft) can already be assured by its third leaf (Tables 5 and 6). With light interception of 44%, LAI 1.64 and tree height of 3.0 m (9.8 ft), the system already yields nearly 42 tonnes/ha in its third leaf, with 90% of fruit having excellent color and apple size averaging 178 g. Tree vigor is under control, with LAI expected to approach 2.00 and light interception 55 to 60% by year 5. Equally important, it will be easy to maintain trees at that vigor for the lifetime of the orchard.

By contrast, incorrect choice of the rootstock and tree density appropriate to a high density planting system is potentially very costly. In their third leaf it is already evident that a block of Sundowner/M.26 trees planted at 3080 trees/ha will never have sufficient LAI and light interception for high productivity (Tables 5 and 6). Although the more vigorous trees are yielding 27 tonnes/ha in their third leaf, their small increase in leaf area index (LAI, 1.00 to 1.11) and % light interception (29.3 to 33.4%) between their second and third leaf shows tree growth has already slowed dramatically. With such inadequate canopy development, sunburn levels are very high (53%).

## GENERAL TRENDS

A primary objective of intensive planting systems is to intercept high levels of light early in the lifetime of the orchard, thereby producing the yields and fruit quality needed to offset orchard establishment costs as quickly as possible. At all sites across Australia the close relationship between light interception and yield was very evident. The highest midseason light interception of the 120 orchard systems measured was 69 to 70%. This was achieved by a 4-row bed system (2804 trees/ha) on M.26 at Orange, New South Wales, and a vigorous double-row east/west Pink Lady V-trellis system on MM.109 (2222 trees/ha) in Western Australia. At such high midseason light interception the fruit quality of both these systems suffered through poor size and color as a consequence of internal shading effects.

The most highly productive apple orchard systems in Australia were characterized by :

- Diurnal midseason light interception of 55-62%
- Leaf area index (LAI) of 2.0 to 3.2 (a measure of leaf density)
- North/south row orientation
- Tree density of 1300 to 2300 trees/ha (526 to 931 trees/acre)
- Regular annual yields of 44 to 88 tonnes/hectare

Although these systems were the most productive, the yield and fruit quality of each of them could be further improved by taking note of several important general trends:

- Yields increased as light interception increased from 55 to 62%
- Fruit quality and packout increased as leaf area index (LAI) declined from 3.2 to 2.0
- Fruit quality and packout improved as tree height was reduced from 4.5 to 3.0 m (14.8 to 9.8 ft)

The leaf area index (LAI) of mature orchards in this study ranged from 0.5 to >3.5 and was representative of the full range of tree vigor occurring within Australian apple orchard systems. At a LAI of 1.5 and lower, there were usually excessively high levels of sunburn damage to fruit.

North/south row orientation should always be used where possible, and the deficiencies of east/west rows were obvious at sites in Tasmania, South Australia and Western Australia. The poor light distribution of east/west rows was highlighted by Middleton and McWaters (1997) and becomes worse as LAI and tree height increase and as alleyways become narrower.

In the early years of an orchard planting, the higher the tree density, the higher the light interception. As trees age and fill their allotted spaces, planting density becomes a less critical factor influencing light interception. For HDP systems to be highly productive and economically viable, they must therefore intercept a very high proportion of incoming solar radiation within the first 3 years. If not, their full potential advantage is lost at considerable cost through the purchase and planting of high tree numbers.

A majority of the orchard systems in Australia intercepted <60% of diurnal sunlight. Where light interception and LAI of mature trees are low it is difficult to substantially improve productivity. Incorrect rootstock and tree density decisions made at planting cannot be changed a few years later unless the orchard is totally replanted. This is costly and impractical. Heavy pruning and/or the application of additional water and fertilizer are undesirable tree management options, which in most cases will likely have relatively little beneficial effect on the vigor and productivity of mature trees. Similarly, crop load adjustment on dwarf trees will have little influence on improving their growth and vigor once they are mature and have cropped for several seasons and "spurred up."

The problem of insufficient light interception was obvious with many of the systems having low LAI and inadequate canopy development. Even when planted as a 4-row bed system at 2804 trees/ha, M.27 rootstock was of insufficient vigor for Hi Early trees to fill their allotted space at Orange, NSW. By contrast, M.9 (3.0 m tree height) and M.26 (3.3 m tree height) planted at 2286 trees/ha were the most productive rootstocks in this trial, with LAI of >1.80 and light interception of 54 to 60%.

Although increasing tree height has less effect on light interception than does LAI and planting density, the influence of tree height on orchard productivity (especially fruit quality) is very significant. At times of the day when shadows are long (early morning and from mid-afternoon onward), taller trees will have higher light interception and cast their shadows across alleyways and into adjacent rows. During the middle part of the day (1 or 2 hours either side of solar noon) tree height has little effect on light interception but nevertheless can significantly contribute to internal shading and poor light distribution within the canopy.

Substantial yield and fruit quality gains are therefore best achieved by maximizing the orchard surface area covered by the external fruit producing canopies of trees and not by increasing tree height. High density plantings of short trees have a larger external surface area exposed to light and a lower volume of "poorly illuminated" canopy than lower-density plantings of tall trees. Alleyways are an essential yet

## TABLE 6

The yield and sunburn incidence of commercial apple orchard systems in Western Australia (May 2000).

| System | Rootstock | Tree density (trees/ha) | Sunburn (%) | Yield per tree (kg/tree) | Yield per area (t/ha) |
|---|---|---|---|---|---|
| Sundowner (vase) | N. Spy | 270 | 7.3 | 205.2 | 55.4 |
| Sundowner | MM.104 | 800 | 8.3 | 106.4 | 85.1 |
| Sundowner | MM.106 | 800 | 14.9 | 84.4 | 67.5 |
| Sundowner (3rd leaf) | M.26 | 3080 | 53.0 | 8.8 | 27.2 |
| Pink Lady | MM.106 | 1000 | 15.5 | 43.2 | 43.2 |
| Pink Lady (3rd leaf) | MM.106 | 2222 | 21.3 | 18.8 | 41.8 |
| Pink Lady V trellis (3rd leaf) | | 4400 | 31.0 | 10.0 | 44.6 |

inefficient feature of orchards, representing areas of land that are nonproductive. Despite this, the contribution of alleyways in providing gaps for light penetration in the orchard is important and should not be underestimated.

Where trees are overvigorous with light interception >60% and LAI approaching 3.0 and above, apple orchard yields and fruit quality improvements will occur with control of tree vigor and attention paid to individual tree structure, pruning, leaf distribution and branch orientation. Vigor control techniques such as summer pruning, cincturing (girdling), root pruning and regulated deficit irrigation (RDI) are appropriate in these situations. Reductions in tree height from >4.0 meters to 3.0 meters will reduce light interception early and late in the day but also reduce the deleterious effects of shadows cast across alleyways impinging onto adjacent rows. It is far more desirable and efficient to increase light interception by planting shorter (3 m) trees at higher densities, rather than base orchard systems on trees of, or exceeding, heights of 3.5 to 4.0 meters.

It is impossible to compare apple orchard system productivity between sites across Australia in terms of rootstock and planting density. The performance of apple rootstocks varies markedly across Australia due largely to variations in climate, soil and tree management. Furthermore, the results show it is the interactive effect of rootstock x planting density on leaf area and light interception that influences orchard productivity. It is measurements of LAI and % light interception which can and ultimately should be used to compare, predict and improve orchard productivity in all apple producing regions of Australia.

The high value apple varieties currently grown such as Pink Lady, Red Fuji, Gala and its strains must all be marketed to meet specific red color (blush) requirements. To grow these varieties in systems that intercept more than 60% of diurnal sunlight is too likely to be at the expense of fruit color, quality and packout.

## CONCLUSIONS

A suggested vision to aim for in apple orchard system design for high yields and fruit quality is:

- Midseason diurnal light interception of 60%
- Leaf area index (LAI) of close to 2.0 and not so low that there is excessive fruit sunburn
- Tree height of approximately 3 meters (9.8 ft)
- North/south row orientation
- Trees as discrete units with a well-defined leader (whether grown in single rows or as part of a V-trellis type system)
- Tree tops that do not merge and are separated by gaps
- A narrow canopy depth in all directions from which sunlight is incident throughout the day.

The majority of apple orchard systems in Australia intercepted <60% of midseason diurnal sunlight, however many of the newer high density systems were approaching 60% light interception as early as their third leaf. The development of an adequate tree canopy is important in the early management of high density systems under the high light intensities and temperatures experienced in Australian apple producing regions. Trees with insufficient canopy volume to support high yields also tend to produce apples susceptible to sunburn through exposure to radiant heat.

Light interception was an excellent guide to orchard productivity, and the lifetime success or failure of a planting system can be predicted as early as the third leaf, based on midseason measures of light interception and leaf area. Sunlight is free, and it is essential to take full advantage of this resource that is so readily available to all orchardists.

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