Quote: Light interception can be increased by reducing the distance between the rows, increasing the height of the trees and orienting the rows wherever possible in a N-S direction.

Light, Canopies, Fruit and Dollars

John W. Palmer
HortResearch
Nelson Research Center
Motueka, New Zealand

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INTRODUCTION

All plant life depends upon the conversion of light energy into chemical energy via the process of photosynthesis. Fruitgrowers, like all farmers, are dependent on this process to convert the light energy falling on their orchard into the large, juicy, attractive fruit we know as the cultivated apple. There is, however, little indication of large cultivar or rootstock effects on the light saturated photosynthetic rate per unit leaf area. In contrast there are major effects of cultivar and rootstock on leaf area per tree. Therefore the seasonal carbon dioxide uptake by an apple tree would be expected to be related to the leaf area and its disposition in relation to the light and its duration. Several researchers have shown a close relationship between intercepted light and dry matter production from a range of crops, including apples. Intercepted light is the light which is captured by the plant, largely by the leaves. In an apple orchard the majority of the light which is not intercepted falls on the orchard floor and grass alleyway. Dry matter production includes shoots, leaves, fruit and roots. As there is little sale for apple leaves, we will concentrate on the influence of light on the fruit component, not forgetting that the leaves, shoots and roots play a vital role in producing the fruit.

YIELD AND LIGHT

A number of researchers in Europe and the USA have shown a close relationship between light interception and yield of apples. The amount of light intercepted by an apple orchard depends upon two characteristics: 1) the light environment, the amount and angular distribution of the sunlight and 2) the canopy characteristics, the row spacing, orientation, leaf area and the three dimensional arrangement of that leaf area in the orchard.

The light environment is dependent on both the latitude, as this determines the incoming solar radiation above the atmosphere, and the cloudiness of the particular location. The influence of latitude on incoming solar radiation is given in Figure 1. Maximum solar radiation receipt occurs in the latitude band of 25-30^{o}; regions closer to the equator are characterized by high rainfall with its associated clouds, while higher latitude locations have greatly reduced solar radiation receipt due to clouds and the short days during the winter. When comparisons of solar radiation are made over the peak 4 months, differences in radiation receipt between latitudes of 30 to 55^{o} are reduced due to the long day length at higher latitudes during the summer. Nevertheless, receipt of photosynthetically active radiation (PAR) increases by 0.03 GJ m^{-2} per degree of latitude between 55 and 35^{o}. Making some simple assumptions, Wagenmakers (1991) calculated that this could be equivalent to 2.5 t/ha (1.1 ton/acre) per degree latitude. Within a latitude band, continental climates typically have clear skies in the summer while more maritime climates are characterized by cloudier skies. The time from the last spring frost to the first autumn frost determines not only the particular period of the year when crop growth can occur, but also fixes the seasonal pattern of incoming light. (This can obviously be slightly extended in the spring with the use of frost protection.)

In terms of the natural environment, the location of New Zealand is ideal for fruit growing, as it enjoys a long growing season with high solar radiation, adequate winter chill but not excessively high temperatures during the growing season. The latter ensures both adequate color formation on partly red cultivars and reduced respiration rates and little reduction of net carbon dioxide uptake by the tree during the day due to high temperatures.

Once the grower has settled on his particular location, there is little he can do to alter the incoming light environment other than reduce it with hail netting. In contrast, the canopy characteristics are under the grower's control. He can choose the shape, size and characteristics of the canopy and therefore how much of the available light the orchard intercepts. The ratio of leaf area per tree to area allocated per tree (leaf area index; LAI) has the major influence on light interception. Mature modern apple orchards typically have LAIs in the middle of the growing season within the range 1.5 to 2.5 (Jackson, 1980). The three dimensional arrangement of the leaf area can modify the light interception, particularly at high LAIs. Light interception obviously can be increased by spreading the orchard canopy as uniformly as possible over the land; unfortunately this prevents access to the trees for the cultural operations of spraying, pruning and picking. Orchard design therefore has to work within this major physical constraint. The inevitable row structure of the canopy means that light interception can be increased by reducing the distance between the rows, increasing the height of the trees and orienting the rows wherever possible in a N-S direction.

Although the relationship between total dry matter production and light interception is often very tight, the relationship between yield of fruit and light interception shows a greater variability (Figure 2). This is to be expected as the partitioning of carbohydrate into fruit depends upon crop load and the light distribution within the canopy. Obviously following a spring frost event or with a strongly biennial cultivar in the off year, crop load can be dramatically reduced with little change in light interception. In the absence of such adverse events, crop load is regularly altered by the grower's thinning practices—total yield of fruit per tree is reduced in order to increase average fruit size. Therefore, care must be exercised in comparing the relationship between light interception and yield between different orchard systems, particularly where comparisons are made within one season and therefore subject to possible confounding of system with crop load. On the other hand, some of the variation seen in comparisons of light interception and yield genuinely reflect differences in system. Crop load can be altered by the light distribution within the tree; heavy internal shading can reduce flower bud production, fruit set and fruit size. Excellent work has been done by Wünsche et al. (1996) in elucidating the importance of light incidence on spur leaves in different systems.

Even greater care must be used when yield and light interception data are compared across locations or regions as, in this case, location can influence fruit growth and yield via temperature. Temperature can have a major effect on the rate of plant processes, particularly those involving cell division and respiration. Early season temperature during the cell division stage can have a large effect on the final fruit size.

Nevertheless, light interception forms a much more useful basis for comparing trees at different spacings or systems than tree volume or trunk cross-sectional area. If two systems achieve a similar light interception yet differ in yield, it indicates that one system is able to partition more dry matter into fruit than the other, via a better distribution of light within the canopy or via a rootstock effect. Although light interception is frequently recorded in the middle of the season after shoot growth has stopped, comparisons of systems may require measurements throughout the season as the seasonal pattern of light interception may be influenced by system where systems vary greatly in canopy form, e.g., light interception may increase more rapidly in spring on the distributed canopies of a Y trellis than the more concentrated canopy of a central leader tree.

LIGHT AND FRUIT QUALITY

There has been much detailed work over the last 30 years on the influence of light on fruit quality, particularly by Jackson and Palmer in the UK, Ferree, Rom, Barritt and Robinson in the USA and Tustin and Warrington in New Zealand. Consistently across these environments and across cultivars, shading has been shown to dramatically reduce fruit quality. Table 1 summarizes the effects of shading on reproductive and fruit characteristics and Table 2 the effects of shading on leaf characteristics. Interestingly these effects are common across a whole range of perennial fruit species—apples, pears, citrus, peaches, cherries, raspberries (Palmer, 1989).

It is very apparent therefore that reduced light can have serious effects upon the production and external and internal fruit quality of apple trees. Fruit color is often the most sensitive indicator of shading with striped or partially red cultivars and, as such, gives a good indicator of likely differences in internal fruit quality. For fully red cultivars that color even in deep shade the absence of skin color differences can lead to false assumptions about internal fruit quality. Similarly background color has been used successfully in some cultivars as an indicator of maturity—a fully red skin can completely hide differences in background color.

As the effects of shade on fruit and leaf characteristics are so clear, the grower does not necessarily need sophisticated light-measuring equipment to determine whether the canopy has excess internal shading. The fruit quality and leaf characteristics in different regions of the tree can give a clear indication.

ORCHARD SYSTEMS

An orchard system is a combination of management practices relating to rootstock, pruning, tree training, tree spacing and the associated farm machinery. Biologically, however, a system can be understood to manipulate, first, the light interception and distribution and, second, the partitioning of carbohydrate into fruit. To be successful the system must work within the physical constraints of access and the biological constraints of the effect of shading on fruit quality. Horticulturists, however, are great manipulators of the plant kingdom and fruitgrowers are no exception. The emphasis over the last few years has been on manipulation via genetics of the scion and rootstock and via pruning and training. Spur types, particularly of Red Delicious, proved invaluable in the USA, while the Dutch led the way with detailed tree training on M.9 in the slender spindle and its variants. The flirtation with plant growth regulators (PGRs) in the 1970s and ’80s did not result in major sustained use as a tool for canopy manipulation in apple production. There has, however, been a small resurgence of activity in the PGR area of late, although this has been largely restricted to specific control of an aspect of fruit development, e.g., the use of GA_{4+7} to control russet or the use of BA as a fruit thinner.

Although we have seen a major development of different orchard systems over the last 40 years, there have been several common themes to these systems. First, there has been a major emphasis on precocity, partly in response to the need for a more rapid turnover of cultivars. Precocity has been enhanced by planting at higher tree densities on more dwarfing rootstocks, the higher tree densities to increase light interception early in the life of the orchard and the dwarfing rootstock to increase the partitioning of dry matter into fruit. On a mature orchard of Golden Delicious on M.9 in East Malling, up to 65% of the annual dry matter could be consistently partitioned into the fruit. If there is a continual demand for large sized apples it is difficult to see this percentage rising much higher, as some dry matter must be partitioned into leaves to ensure adequate photosynthesis and some into the structure of the tree and reserves to maintain the perennial habit of the tree.

The second major emphasis in modern systems has been upon the production of large, high quality apples. This can be achieved only by ensuring good light penetration into the canopy. Control of vegetative growth is critical here. Vegetative growth has been reduced by the use of dwarfing rootstocks, branch bending, reduced pruning and the greater understanding of the effect of apical dominance. The Lincoln canopy was a very innovative design by an engineer to ensure that the fruit had a short distance to travel from the planar canopy to the catching system. Unfortunately vegetative vigor was excessive from the horizontal branches, as there was no control by apical dominance. Consequently, fruit color of red apples could be maintained only with difficulty by excessive summer pruning.

ECONOMICS

The apple tree canopy has shown itself to be very adaptable to manipulation; it responds reasonably predictably to pruning and branch manipulation; it generally bears ample flowers throughout the tree on all ages of wood from 1-year-old wood to older spurs; it shows good variation between scion cultivars and can be drastically altered by the wide range of available rootstocks. Consequently, there are numerous ways of arranging an apple tree canopy in space and many of these systems have their vigorous human supporters. The bottom line as always is, does the system make money? It is easy for the scientist to either forget the economic aspect or make crude, grossly misleading financial calculations. Financial returns are dependent on the investment and maintenance costs and the value of the harvested crop. Investment costs can vary quite widely from grower to grower depending on the individual costs of trees and support systems. Consequently, the suitability of any system to a particular grower will depend upon the specific individual cost and the make-up of the rest of the enterprise. It also depends upon the capability of the grower to manage the system. Intensive systems tend to demand intensive management, as there is inherently more control being exercised over the tree. If the grower fails to appreciate this management requirement, the system may not perform as well as anticipated and not provide the expected return on investment.

CONCLUSIONS

Total dry matter production and yield of fruit of apple both have been linearly related to light interception. The cultivated apple canopy has shown itself to be very adaptable to canopy manipulation by the use of rootstocks, tree training and pruning, and genetic variation within scion cultivars. As a consequence, there have been numerous orchard systems described which modify the display of the canopy in space and hence the light interception and distribution within the canopy. There are several common threads to many of these modern systems: 1) early cropping, brought about by planting trees closely together on dwarfing rootstocks, ensuring high light interception, 2) the maintenance of good light distribution within the canopy to ensure good fruit quality and 3) maintenance of access for horticultural operations. Although apple tree canopies have been and will be modified in the future, economic considerations will largely determine the prevalence of particular systems within any one area of fruit growing.

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Table 1. Effect of shade on apple flower bud development, fruit set and fruit quality.

Decrease	fruit weight
	fruit red color
	soluble solids concentration
	bitter pit incidence and severity
	sunburn
	flower bud numbers
	skin russet
	fruit set
Increase	shrivel
	fruit firmness

Table 2. Effect of shade on apple leaf structure and activity.

Decrease	leaf photosynthesis
	leaf thickness
	leaf cupping
	leaf mass per unit

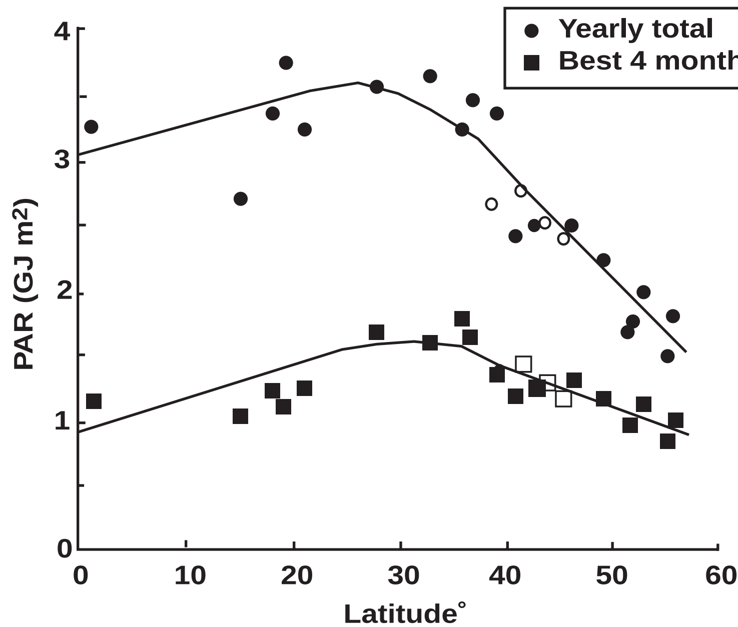

Figure 1. Effect of latitude on the receipt of solar radiation. Data taken from Cooper (1975) and published sources in the UK and New Zealand. New Zealand fruit growing regions are shown as open symbols.

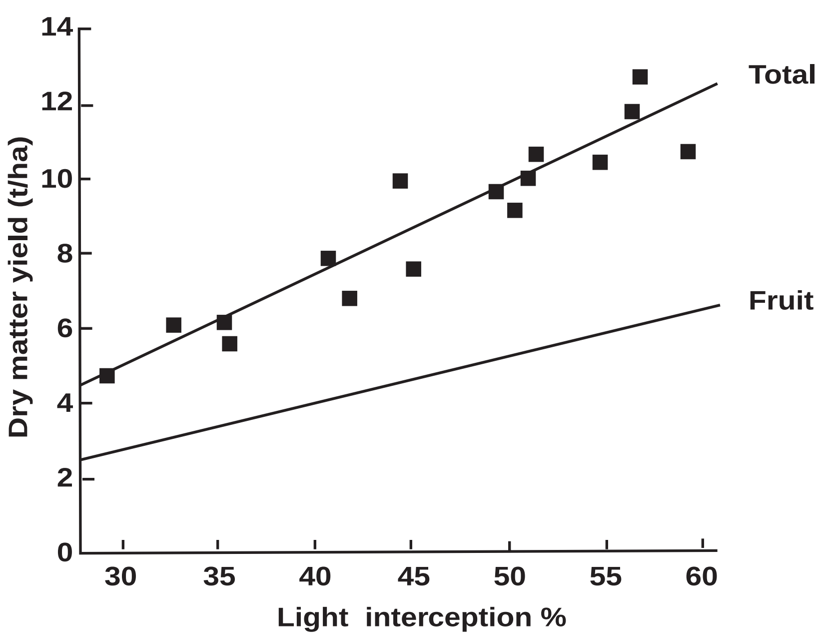

Figure 2. Relationship between light interception and total dry matter production and yield of fruit of Golden Delicious/M.9 at East Malling.