Light relations in orchard systems

Promotoren: dr. ir. R. Rabbinge
hoogleraar in de produktie-ecologie,
met bijzondere aandacht voor de plantaardige produktie

dr. J. Tromp
hoogleraar in de tuinbouwplantenteelt,
met bijzondere aandacht voor de overblijvende gewassen

Light relations in orchard systems

P.S. Wagenmakers

Proefschrift

ter verkrijging van de graad van doctor
in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus
dr. C.M. Karssen
in het openbaar te verdedigen
op woensdag 18 januari 1995
des namiddags te vier uur in de Aula
van de Landbouwuniversiteit te Wageningen

CIP-data Koninklijke Bibliotheek, Den Haag

Wagenmakers, P.S.

Light relations in orchard systems / P.S. Wagenmakers -
[S.1. : s.n.]
Thesis Wageningen. -With ref. -With summary in Dutch.
ISBN 90-5485-340-9
Subject headings: orchard systems / light interception

Cover

Appelboom in bloei (1912), Pieter Mondriaan

Stellingen

1. Een hogere plantdichtheid bij vruchtbomen dient te worden gecombineerd met een lage verhouding van padbreedte tot afstand in de rij.

   Dit proefschrift

2. Een vierkant plantverband in boomgaarden geeft de hoogste lichtonderschepping en de meest regelmatige lichtverdeling. Dit leidt tot een hoge produktie van goede en uniforme kwaliteit.

   Dit proefschrift

3. Hoge vruchtbomen met een lage bladerdichtheid zijn beter dan lage, compacte bomen.

   Dit proefschrift

4. In de fruitteelt zijn meerrijsystemen in driehoeksverband qua lichtbenutting minder gunstig dan meerrijsystemen met looppaden of enkele rijen.

   Dit proefschrift

5. Een wiskundige basis onder hypotheses bevordert het kwantitatief begrip van planten en hun respons op de omgeving.

   J.H.M. Thornley, 1976. Mathematical models in plant physiology. Academic Press, London New York San Francisco, pag. 3.

6. Niets is zo praktisch als een goede theorie.

   Emanuel Kant (1724-1804)

7. Bij de reorganisatie van het praktijkonderzoek dient onderkend te worden dat de betrokkenheid van een proefstation bij de praktijk belangrijker is dan de grootte van de instelling.

8. De stelling dat de verdeling van het landbouwkundig onderzoek in Nederland over twee verschillende directies binnen één ministerie ondoelmatig is, heeft nog niets aan kracht verloren.

   Stelling bij proefschrift van S.J. Wertheim, 1971, Med. Landbouwhogeschool Wageningen, 71-17.

9. De herverdeling van arbeid onder mannen en vrouwen heeft een positieve invloed op het welzijn van de samenleving.

10. Het is belangrijk alle grote gedachten opnieuw uit te spreken, zonder te weten dat ze reeds uitgesproken zijn.
    Elias Canetti (1905-1994)
11. Oranje vlaggen op kinderfietsjes bevorderen risicovol gedrag van automobilisten.
12. De afstand Goes-Wageningen is korter dan de afstand Wageningen-Goes.

Stellingen behorende bij het proefschrift van Patricia Wagenmakers:
'Light relations in orchard systems'.

Wageningen, 18 januari 1995

Abstract

The optimization of light interception is essential for the production of high-quality fruit. High light interception is required for high yields, whereas insufficient light exposure may lead to inferior flowering and a reduction of many characteristics of fruit quality. Orchard configuration is important for the manipulation of light utilization. In this context, the influence of planting density, arrangement, tree size and shape on light interception was quantified in a model approach. The results were evaluated with the use of datasets from experiments with apple.

From the results of the calculation of light absorption and canopy photosynthesis, it could be inferred that early cultivars having a growing season of only four months achieve about the same potential production over a wide range of temperate regions. The production of cultivars with a longer season would, however, increase by at least one tonne fruit (fresh weight) per ha for every degree lower latitude. On the other hand, production at low latitudes may suffer from higher respiration costs.

A model for the assessment of light transfer through trees was used to analyse the influence of density, planting system, and tree size and shape. It was concluded that trees with a conical shape have better light penetration into the lower tree parts than have those with parabolic or cylindrical shapes. Light interception and the amount of well-illuminated canopy increase with planting density particularly if leaf density of the crowns is not increased. Systems with a low ratio of between-to-within row distance (rectangularity) should intercept light very efficiently.

In experiments, planting density was found to be the most important orchard factor for production per ha, which was actually due to leaf area. Systems at low rectangularities produced considerably more well-coloured fruit than did those at higher rectangularities. The productivity of three-row bed systems on a triangular design lagged behind that of other systems. A tall but open tree was found to produce more well-coloured fruit than lower trees with a higher leaf density did. It is concluded that for fruit growers light interception is a key factor for the optimization of orchard management, that can be manipulated by planting density, planting system, and tree size and shape.

Key words: apple, light, planting density, planting system, potential production, simulation model, tree height.

Account

The chapters 2–7 in this thesis have been published in or submitted to various journals.

Chapter 2. Wagenmakers, P.S., 1991. Planting systems for fruit trees in temperate climates.
Critical Reviews in Plant Sciences, 10: 369–385.

Chapter 3. Wagenmakers, P.S. Effect of latitude on potential apple production. Submitted to Agricultural and Forest Meteorology.

Chapter 4. Wagenmakers, P.S., 1991. Simulation of light distribution in dense orchard systems. Agricultural and Forest Meteorology, 57: 13–25.

Chapter 5. Wagenmakers, P.S. and Rabbinge, R. Optimal spacing of apple trees in relation to light distribution - a model approach. Submitted to Agricultural and Forest Meteorology.

Chapter 6. Wagenmakers, P.S., 1988. Effects of planting system, tree shape, and additional summer pruning on growth, production and flowering of apple trees at high plant densities. Journal of Horticultural Science, 63: 383–392.

Chapter 7. Wagenmakers, P.S. and Callesen, O. Light distribution in various orchard systems and its relation to production and quality of apple at two latitudes. Submitted to Journal of Horticultural Science.

Voorwoord

Om een echte mus te worden, moet je door mussen worden grootgebracht. Jonge mussen tsjilpen pas als mussen wanneer ze oudere mussen horen. Ze leren het niet van een vink of een spreeuw. Deze metafoor is ook van toepassing op het hier gepresenteerde proefschrift. Zonder de stimulerende begeleiding van Rudy Rabbinge en Jan Tromp was het nooit zo ver gekomen. Hen wil ik in de eerste plaats danken voor hun inspirerende ondersteuning. Ook de collega's op het Proefstation, met name de afdeling Teelt/Economie, ben ik zeer erkentelijk. Bob Wertheim heeft het belang van een theoretische onderbouwing van praktische problemen altijd erkend en verdedigd. Hij is van onmisbare waarde geweest voor de opzet, uitvoering en afronding van dit onderzoek. Frans Nijsse, Alfred van de Waart en Marcel Tazelaar hebben vele lichtmetingen, bladtellingen en oogstwaarnemingen verricht. Zonder hen was dit werk ondenkbaar. Zij vormden bovendien mijn "praktijkgeweten". Mijn dank geldt ook de vele studenten en stagiairs die vanaf 1985 aan dit onderwerp hebben gewerkt. De statistische analyses zijn verricht door Jan van Dieren en later zijn opvolger, Eric van Remortel. Discussies met statistici hebben mijn wetenschappelijk leven op een bijzondere manier verrijkt en mondden niet zelden uit in filosofische beschouwingen van onderzoek, fruitteelt en samenleving.

De Engelse correcties zijn (in sympathiek groen) uitgevoerd door mevr. I. Seeger-Wolf. De afbeelding op de omslag is van Pieter Mondriaan. Zijn stijl van het terugbrengen van voorwerpen tot abstracte eenheden sluit aan bij het modelleren zoals toegepast in dit proefschrift. In dit opzicht staat Mondriaan model voor de verwevenheid van kunst en wetenschap.

Met de komst van Daniël en Wietse leek de afronding van het proefschrift niet meer vanzelfsprekend. Toch zijn ook zij drijvende krachten geweest om dit werk door te zetten. Het ouderschap werd gelukkig gedeeld. Kees hielp me bovendien bij het optimaliseren van computerprogramma's. Hij is tenslotte verantwoordelijk voor het opmaken van dit proefschrift. Mijn ouders legden de basis voor het benodigde doorzettingsvermogen. Zij stimuleerden me om te leren en, later, werk en gezin te combineren. Ze hebben dat ook daadwerkelijk ondersteund door op gezette tijden de zorg voor de kinderen op zich te nemen. Ook andere familieleden en vrienden wil ik daarvoor bedanken. De vriendinnen nemen een speciale plaats in. Met name wil ik Irma Jorritsma noemen, met wie ik de ervaringen van onderzoek en moederschap kan delen en die me op beide gebieden inspireert.

Contents

1 General introduction . . . 11
  Aim of the thesis . . . 14
  Outline of the thesis . . . 15

2 Environmental and cultural factors defining fruit production . . . 17
  2.1 Introduction . . . 17
  2.2 Recent developments in intensification . . . 18
  2.3 Factors defining productivity . . . 22
    Environmental factors . . . 22
    Cultural factors . . . 25
  2.4 Conclusions . . . 35

3 Effect of latitude on potential apple production . . . 37
  3.1 Introduction . . . 38
  3.2 Methods . . . 39
    Radiation and gross photosynthesis . . . 39
    Phenology . . . 40
    Dry-matter distribution . . . 41
    Gross and net photosynthesis . . . 43
  3.3 Results . . . 44
    Effect of radiation . . . 44
    Effect of temperature and respiration . . . 48
  3.4 Discussion . . . 51
    Radiation . . . 51
    Respiration . . . 52
    Potential and actual production . . . 53

4 Simulation of light distribution in dense orchard systems . . . 57
  4.1 Introduction . . . 57
  4.2 Structure of the model . . . 58
    Tree architecture . . . 59
    Light transmission . . . 60
    Evaluation of the consistency of the model . . . 61

4.3 Results . . . 61
Verification of the model . . . 61
Effect of row configuration . . . 64
Effect of tree shape and leaf characteristics . . . 65
Effect of tree spacing . . . 66
4.4 Discussion . . . 68

5 A model approach on optimal orchard design . . . 71
5.1 Introduction . . . 71
5.2 Calculating light transmission in planting systems . . . 73
Light transmission . . . 73
Tree dimension and planting system . . . 75
5.3 Validation of the model . . . 76
Light and leaf-area measurements . . . 76
Comparison between estimated and measured results . . . 77
5.4 Simulation results . . . 79
Rectangularity . . . 79
Alley width . . . 80
Tree diameter . . . 81
5.5 Discussion . . . 83
Significance of the model . . . 83
Light distribution in planting systems . . . 84

6 Planting system and pruning regime . . . 87
6.1 Introduction . . . 87
6.2 Material and methods . . . 90
6.3 Results . . . 92
Growth . . . 92
Production . . . 92
Flowering . . . 95
6.4 Discussion . . . 96

7 Production and fruit quality at two latitudes . . . 101
7.1 Introduction . . . 101
7.2 Materials and methods . . . 102
Orchard design . . . 102
Fruit production and leaf area . . . 103
Interception of global radiation during the season . . . 103
Light interception and distribution per planting system . . . 104
Simulation of potential production per latitude . . . 104

7.3 Results . . . 105
Growing season . . . 105
Seasonal pattern of intercepted radiation . . . 107
Light interception and distribution of planting systems . . . 107
Light distribution within the crown . . . 108
Leaf area index . . . 109
Fruit production . . . 111
Fruit weight and colour . . . 112
Simulation of potential production . . . 113
7.4 Discussion . . . 114
Influence of latitude . . . 114
Influence of orchard geometry . . . 115

8 General discussion . . . 117
8.1 Importance of light . . . 117
Potential production . . . 117
Dry-matter distribution . . . 118
8.2 Modelling light interception by planting systems . . . 119
8.3 Modelling fruit production . . . 120
8.4 Practical applications . . . 122
Planting density . . . 122
Planting system . . . 123
Tree height . . . 124
8.5 Future research . . . 125

Summary . . . 127

Samenvatting . . . 131

References . . . 137

Curriculum vitae . . . 151

1 General introduction

Apples have been cultivated for ages. They probably originate from South West Asia, where a diversity of species and varieties has been found in a wild state at altitudes of 900 to 1300 m. The apple accompanied early man in his colonization of the world and was already familiar to prehistoric inhabitants of Europe. The northern European nations (i.e., Germanic, Celtic and Slav) all have names for the apple containing Ap, Af, Ob, etc., which suggests that they used the same name before they were segregated as a result of migration (Hall and Crane, 1933).

Early orchards were in fact fruit meadows: widely spaced trees were planted in grass or interplanted with gooseberries or currants. Several varieties of

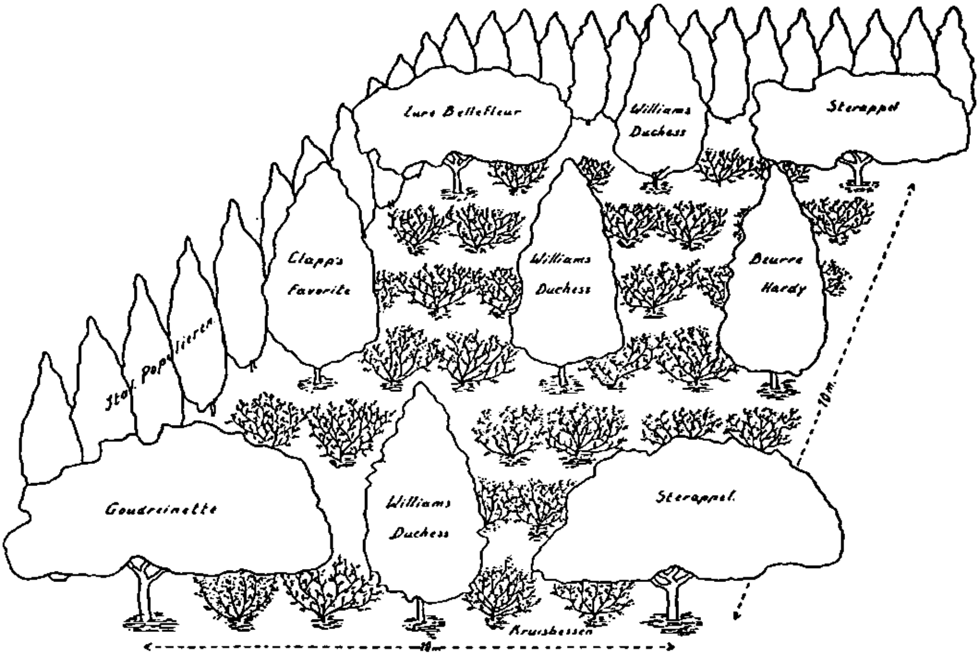


Figure 1.1

Illustration of a planting design for a fruit garden with apple (square planting, 10 x 10 m), with interplanting of pear (at 5 m), understorey of gooseberry, and windbreaks of Italian poplar, 1910–1920 (from van Soest and Robijn, 1948).

apple and pear were planted together. Figure 1.1 illustrates this for a typical Dutch orchard at the beginning of the twentieth century. Although the ornamental and ecological values were unquestionably high, the plantations were run as subsidiary business. The trees, on seedling rootstock, had to be trained for 10 or even 20 years before they came into full production. Moreover, their bearing patterns were very irregular. These plantations gradually disappeared and made way for commercial fruit holdings, although in German-speaking countries the 'Streuobstbau' reminds us of this past. Modern fruit growing has been developed towards specialized systems at high planting densities with small trees, coming early into bearing and aimed at regular and high yields of good quality. This development continues. Today, apple orchards of 3000 trees per ha can produce fruit from the second year after planting and pay back the high investments within 10 to 15 years. This important feature of higher densities allows the grower to reduce the lifespan of his orchard which in turn enables him to take an early advantage of new cultivars, mutants, rootstocks, or planting systems.

The introduction of dwarfing rootstocks provided the basis for controlled tree growth, indispensable for small planting distances. In addition, dwarfing rootstocks induce early cropping, which in turn is a growth-reducing factor. The increase in production was further enhanced by improved crop-management methods, such as more refined control of pests and diseases, and trickle irrigation or fertigation to cope with the competition for water and nutrients between trees at smaller distances. In some cases, growth retardants are used as well, but these are becoming a less attractive option, which is due to general pressure from consumers for foods to be produced with minimal input of chemicals. Although prohibition of the use of growth retardants does not interfere seriously with intensive apple growing, the situation is more difficult for pear. A really dwarfing rootstock for pear comparable to those for apple has not yet been found. Today, intensive pear plantings rely on the availability of growth retardants, such as chloromequat.

Light interception is the forcing factor for photosynthesis and determines the productivity of fruit trees. In addition, light is involved in the flower-initiation process and in a number of important fruit-quality parameters, such as colour, flavour, and the sugar:acid ratio (Arthey, 1975). The influence of light is not restricted to the current year, but even to some extent determines fruit production in the subsequent season via e.g. its effect on flower-bud formation (DeJong and Day, 1991). Fruit production per ha has been found to be correlated with light interception in a number of studies, as reviewed by Jackson (1980) and Palmer (1989a). It is stated that production increases with light interception up to about 70% of available light. Apart from inferior flower-bud formation, insufficient light exposure may lead to a reduction of fruit size and colour, and to lower contents of soluble solids and starch content in the fruit, whereas firmness and total acidity may be increased (Cain, 1971; Proctor et al., 1975; Robinson et al., 1983; Robinson and Lakso, 1991; Palmer et al., 1992). Apples of high commercial quality may need even more than 50% light exposure (Jackson, 1970). Consequently, orchard management aims at a high level of light interception coupled with a minimum of within-tree shading.

Orchard configuration is an important factor for light utilization. Light interception can be increased by planting at higher tree densities or decreasing the ratio of between-to-within row spacing. For each arrangement, a suitable tree size and shape has to be chosen. There are three basic methods for planting trees (Figure 1.2):

- The square planting: the distances between and within the rows are the same. In early times, this full-field design was already recommended for fruit meadows for reasons of efficient light use.
- The rectangular design: distances within the row are smaller than between the rows. The number of trees is not necessarily the same as in square plantings. Current single rows are representatives of this system.
- The triangular design: every three trees form a triangle. In this way, more trees per ha can be accommodated per ha than with a square design. The 'North-Holland' three-row bed is an example. Many multi-row systems with walking paths between trees within the bed take an intermediate position between triangular and rectangular designs.

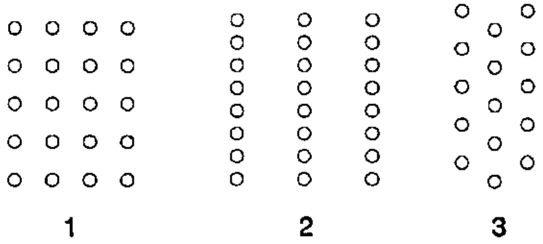


Figure 1.2

Basic methods for planting fruit trees: 1) square; 2) rectangular; 3) triangular.

The interception and distribution of light differs considerably between the various systems of planting, leading to differences in yield and fruit quality. Growers have discussed the benefits of many combinations of arrangement, density, pruning and training for many years (Wertheim and Lemmens, 1973; Goedegebure, 1978; Werth, 1981; Wertheim, 1990), but the interactions between the various factors are manifold and difficult to deal with in field experiments. As a consequence, the discussions never end. More insight into the quantitative relationship between light, planting system, and fruit production is therefore needed to provide growers with a basis for decisions on planting system.

Aim of the thesis

The study reported in this thesis concerns the relationship between planting system and light interception. The light interception of an orchard system is determined by incoming and transmitted light, which can be measured with meters that are sensitive to wavelengths in the range of photosynthetically active radiation (400–700 nm). Light interception can be modelled by predicting the behaviour of light fluxes as a function of incoming light, according to the intensity and direction of the solar rays, and of light absorption, reflection, and transmission on the basis of the geometrical and optical characteristics of the canopy. The main aim of this way of modelling is to obtain an understanding of processes at the canopy level by describing processes at the lower level of the tree (Thornley and Johnson, 1990). Several models describing light transmittance have been developed, based on the exponential relationship between transmitted light and geometric and optical properties of the canopy, as was first presented by Monsi and Saeki (1953). The complexity of a model depends on the number of dimensions used to describe the canopy. Many arable crops can be simply represented by one-layered, homogeneous canopies. For orchards, however, a three-dimensional approach is needed, to deal with individual trees of a given dimension and shape in different planting densities and systems. For validation of the model, experimental data on light interception in relation to productivity and fruit quality in different orchard systems are collected. Furthermore, spacings theoretically optimal from the standpoint of light interception and use are compared with other, more practical designs with respect to production and fruit quality.

Outline of the thesis

The importance of environmental and cultural factors affecting fruit production are reviewed in Chapter 2. The potential production of fruit on the basis of light absorption as estimated by simulating seasonal crop photosynthesis for different cultivars and latitudes in the temperate zone is discussed in Chapter 3. The effect of temperature on various phenological aspects and respiration is also investigated.

Chapters 4 and 5 report the studies on the effect of planting system on light distribution by calculating light transmission through three-dimensional tree structures. The model results are validated against light measurements in different planting systems of apple and pear. Chapter 4 deals with the effects of leaf density on canopy light interception in relation to planting density, tree shape, and tree height on different row systems. Chapter 5 describes a model analysis of light interception and within-tree light distribution for a range of theoretical and practical planting systems.

Chapters 6 and 7 deal with experimental results on interactive effects of planting system, density, and tree shape. Chapter 6 includes the arrangement of trees of a given size and shape in single-row and multi-row designs in connection with tree growth, flowering, regularity of bearing, and yield. Chapter 7 also discusses the effect of incoming light on production as worked out for an experiment conducted at two latitudes. The productivity and fruit quality of the square planting is also evaluated and compared with those for more rectangular plantings at different tree densities and heights. The importance of light for orchard configuration as well as the possible applications to apple growing is discussed in Chapter 8.

2 Environmental and cultural factors defining fruit production

Abstract

Developments in intensification of pome-fruit orchards have led to changes in orchard design. Dwarfing rootstocks increase the proportion of harvestable yield. Precocious and high yields are also obtained with high light utilization, which can be achieved by manipulating planting density and planting system. To demonstrate this, hedgerows, multi-row systems, and various trellised systems are compared with full-field systems and homogeneous canopies. Light distribution is more uniform at low rectangular designs, which favours productivity, but a higher rectangularity (e.g., single rows) may be preferred if light penetration into the centre of the rows becomes too low. The importance of row orientation for various planting systems and the effect of tree design on growth and productivity are discussed. Physiological implications are indicated briefly. Conclusions are drawn on optimal orchard designs in temperate climates.

2.1 Introduction

Current orchard systems aim at precocious and high yields of good-quality fruit. This goal can be achieved by intensification of tree density and by using rootstock-cultivar combinations that allocate high amounts of assimilates into fruit. The advantages of intensification are precocious yields, higher returns, and lower labour costs due to smaller trees, and, as a consequence, the feasibility of early renewal of the orchard. The latter makes it possible to go along with new developments, such as other cultivars, clones, mutants, rootstocks, or planting systems (Jackson, 1985; Goedegebure, 1989). Attainment of the ultimate goal of an early and high yield will depend on environmental factors and geometrical, optical, phenological and genetic properties of the individual tree or the orchard system. The influence of these productivity-defining factors is reviewed here. Productivity may be reduced by the occurrence of pests and diseases, but it is assumed that such a reduction is not due to the planting system.

The emphasis is on apple. Pears have shown a similar trend in intensification to that seen for apple, but are generally planted at lower tree densities, due to the lack of sufficiently dwarfing rootstocks. Consequently, pear trees are less precocious and often crop less regularly than apples. Moreover, pears do not feather as well as apples in the first year after budding, which delays an early production and hence early return of the investment. Comparable dwarfing rootstocks or cultivars with a favourable allocation pattern between fruit and vegetative growth are still lacking for plums and cherries, although promising rootstocks may become available for the latter (Tréfois, 1989).

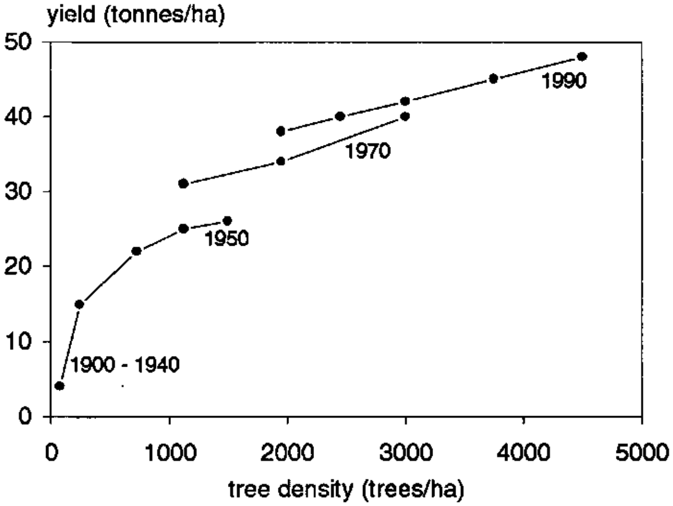
2.2 Recent developments in intensification

The advantages of intensive fruit growing, as expressed in precocious yields, have long been known from the so-called cordon systems, used in fruit gardens of monasteries or castles between the fifteenth and eighteenth centuries in Europe. Cordon trees have a trunk giving rise to one or two leaders ('single' or 'double' cordons) with very short fruiting laterals (three to ten nodes). Horizontal, vertical, and oblique cordons are termed according to the direction of the leaders. The first of these had an ornamental rather than a productive function and such trees were widely spaced along borders. Oblique and vertical cordons have been planted at narrow within-row spacing (minimum distances 30 to 50 cm) along a wall or trellis. The head of the royal French gardens of Louis XIV, La Quintinye, recommended an alley width of 2.5 m (Hugard, 1981), which meant that historical cordon systems attained densities of 8000 to 10,000 trees per ha. The dwarfing quince and apple rootstocks were already in use for pear and apple, respectively. Oblique and vertical cordons were commercially applied in specialized fruit farms until the twentieth century, too. These intensive systems involved much skilled labour (Wertheim, 1981). Only training and pruning, needed for control of vegetative growth and of regular cropping, were estimated to require at least 200 hours per ha, particularly during summer. Labour intensity was one of the reasons that the cordons vanished from commercial orchards and were replaced by more extensive systems. The 'Ferraguti' system designed for pear in Italy was a mechanically pruned vertical cordon system in the 1930s with 2300 to 4000 trees per ha, but disappeared because machinery access gave problems (Sansavini, 1975).

In the beginning of the twentieth century, large standard trees on vigorous rootstocks were very common. These trees had a trunk of 1 to 2 m, crown dimensions of 10 m or more, and were planted in a density of 100 trees per ha or less in square or triangular designs. Mean productivity and fruit quality were low. A full-grown standard tree could easily produce 400 kg, but since the production pattern was irregular, average yield per ha was greatly reduced. In the initial years, the trees were heavily pruned to create a strong framework, which delayed the start of the productive period by at least ten years. An undergrowth of grass on heavy clay soils or small fruit or vegetables on other soils was a typical feature of these orchards. Since final light interception could be very high, growers were even warned against using too-narrow planting distances, to prevent yield reduction of the understorey plants.

Several orchard factors led to a intensification of fruit growing, as is demonstrated with developments in The Netherlands (Wertheim, 1977, 1981). Figure 2.1 shows the increase in tree number and production per ha, and in labour efficiency (including cultural practices, harvesting, and grading after harvest). The start of intensification came with the selection of rootstocks prepared by Hatton at East Malling Research Station in the 1920s. This improved a correct estimation of vegetative growth. The application of dwarfing rootstocks led to precocious and high yields and was associated with a reduction in tree size, which decreased the fraction of unproductive shaded canopy (Heinicke, 1964). New training systems were invented, starting with the bush or central-leader tree, probably introduced from the USA. It was similarly shaped but planted at more dwarfing rootstocks and arranged at closer spacings than standard trees. Since the trunk height was only 0.5 m, the undergrowth disappeared. Successful bush orchards, planted at a density of about 250 to 750 trees per ha, could produce four to five times more than standard-tree orchards, and labour efficiency increased even more. By 1950, standard trees had completely vanished from commercial orchards.

Orchard profitability was also increased by a system of interplanting temporary 'filler' trees on dwarfing or moderately vigorous rootstocks between 'permanent' larger trees on vigorous rootstocks. In this system, bush trees were interplanted between standard trees or smaller bush trees between larger ones. The former were planted on less vigorous rootstocks and were pruned less severely. Because growers were aware that the highest yield was always obtained the year before grubbing of the filler trees, they finally grubbed the permanent trees, and filled the empty spaces with trees on dwarfing rootstocks.



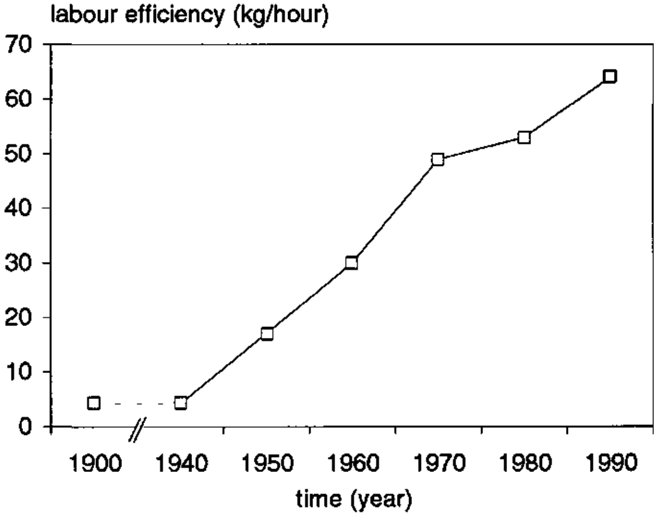


Figure 2.1

Changes in time of yield (upper) and labour efficiency (lower) in The Netherlands. Data from Dutch Agricultural Economics Research Institute.

Further improvement in orchard productivity and labour efficiency came with the application of the spindlebush around 1950. Originating from a filler tree in the interplanting system, it was first introduced in Germany in the 1930s. The spindlebush tree was about 2 m high and had a maximum width of 1.5 m, a central axis with fruiting laterals, and a conical shape. It was grafted on M.9 rootstock and was supported by a stake, which made heavy pruning to create a supporting frame unnecessary. Typical Dutch spindlebush orchards were planted at about 1250 trees per ha (spacing 4 x 2 m) between 1950 and 1970. In this period, the increase in productivity was also due to the application of more productive cultivars ('Golden Delicious'), although similar tendencies occurred with cultivars that were available for many decades such as 'Cox's Orange Pippin'. Furthermore, improved control of diseases and pests has contributed to productivity increase.

From the early sixties onward, tree management was further improved by the application of the slender spindle. Tree training in the initial years included bending of branches instead of pruning, which advanced the fruiting stage to about three years after planting. Tree size and leaf density were reduced by removal of older or excessively vigorous laterals, which improved light penetration. Tree size and density have gradually been modified and current slender-spindle orchards are found in a range of densities between about 2000 and 4500 trees per ha. The increase in density was proportional to the increase of both productivity and labour efficiency. In 1990, orchards with 2000 and 4500 trees per ha produced 38 and 48 tonnes per ha and labour expenditure amounted to 62 and 68 kg per hour, respectively.

Due to a shortening of the unproductive period and an increase of production, the current average orchard lifespan has been reduced to about 15 years for apple (Goedegebure, 1986). Comparable changes in orchard management have occurred in other countries, but the degree and success of intensification differ widely. They are influenced by economic factors such as interest rates, costs of trees and tree-support material, farm size, and demands for ease of mechanical harvesting, and further by tree quality at planting, availability of appropriate rootstocks, and potential yield (Jackson et al., 1981). Moreover, differences in managerial capacity can cause large variations in crop yield.

Extrapolation of Figure 2.1 suggests a further benefit of higher densities. Recently, systems with densities between 8000 and 18,000 trees per ha have been reintroduced on a small scale in Germany and The Netherlands. Preliminary results indicated apple yields of about 60 tonnes per ha in the second year after planting, achieved with about 60% light interception for the given range of densities (Wagenmakers, 1991a). More intensive systems have been investigated. An extreme case is formed by meadow orchards, where fruit-bearing shoots were harvested and the tree was cut back to about ground level every other year. By planting 70,000 trees per ha and use of chemical growth control, yields of 100 tonnes per ha could be attained every alternate year (Luckwill, 1978). Although this system is not practical for crops that do not flower and fruit well on current-year's shoots, it may be so for peaches (Erez, 1978).

2.3 Factors defining productivity

Canopy photosynthesis is the main factor underlying crop productivity. To estimate potential production, the available energy input in a particular environment must be integrated over the duration of the growing season, and the light energy conversion, being a function of light interception and partitioning of assimilates to fruit, must be known (Cooper, 1975). The influence of environmental factors and geometric properties of the orchard on potential production will be analysed.

Environmental factors

Temperature

Temperature influences the duration of the potential fruit growing season. Annual mean daily air temperature is a linear function of latitude with a slope of −0.45 per degree between 10 and 55° (Charles-Edwards, 1982). This leads to advanced leafing and blossoming time at lower latitudes. Flower development starts 2.5 days earlier per degree lower latitude, according to studies for apple between 43 and 65° N (Gardner et al., 1922; Heim et al., 1979; Wagenmakers and Callesen, 1989). For any given cultivar, the duration of the growing season tends to be rather constant (Wagenmakers and Callesen, 1989), but warmer climates offer the possibility to grow cultivars that need a longer season.

Furthermore, growth is often more abundant at higher temperatures. For apple trees on M.9, receiving normal pruning practice, a 25 and 40% increase in leaf area has been reported to occur, going from 55 to 51 and from 51 to 43° N respectively (Palmer et al., 1989; Wagenmakers and Callesen, 1989). The reverse observed for trees on M.27 (Palmer et al., 1989) was probably due to the poor performance seen on this rootstock under warmer climatic conditions. Fruit growth rate is more rapid and fruit size is promoted at higher temperatures, leading to differences in internal fruit quality (Abbott, 1984; Palmer et al., 1989; Wagenmakers and Callesen, 1989).

The influence of temperature is obvious when different regions are compared, but there is less evidence that differences in temperature distribution between various orchard systems influence tree behaviour. Trees in hedgerow systems were found to exert little influence on the temperature profile (Landsberg et al., 1973). However, intensive plantings sometimes show better fruit set than wide plantings do. This can be explained by a shorter distance between pollinizer and cultivar and a more sheltered environment leading to a better microclimate (Preston, 1956; Free, 1962).

Light

The visible light spectrum, including the photosynthetically active radiation (PAR), constitutes about 46% of the global radiation (Weiss and Norman, 1985). In the present article, the term 'light' refers to this component. The incoming light is essential for physiological and morphological aspects of tree and fruit growth and development. Total and fruit dry-matter production are related to light interception (Monteith, 1977; Palmer, 1989a). A shortage of light affects fruiting processes more than it does vegetative growth, and reduces fruit-bud formation, fruit set, size, and colour as well as eating quality (Jackson, 1978). Moreover, various aspects of fruit quality are reduced more by light shortage than production per ha (Tromp, 1984; Sansavini et al., 1981). Light interception closely approaches to maximum by one month after bloom so light shortage may occur from early in the season (Rom and Ferree, 1984a; Barrit and Rom, 1987; Lakso and Goffinet, 1987; Wagenmakers and Callesen, 1989).

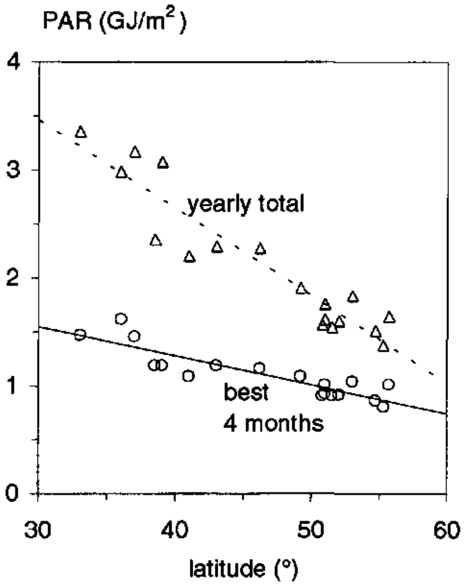


Figure 2.2

Incoming PAR as a function of latitude. Data from Black (1956), Callesen (pers. commun.), Grace (1988), Palmer (pers. commun.), and Roy. Dutch Meteorol. Inst.

The annual mean values for daily light integrals decrease linearly with latitude in the temperate zone from 35 to 55° (Figure 2.2). The slope of the regression for annual values is -0.081 GJ m^{-2} light per degree latitude. However, a greater daylength at higher latitudes during the summer reduces differences in incoming light during the actual season. Accounting for the four months with highest light integrals (May through August for the northern hemisphere), the regression slope is -0.027. For this period, the slope value for incoming light in the absence of an atmosphere (Angot's value) is only -0.007 for the given range of latitudes. So, the relatively higher light integrals at lower latitudes are caused by less cloud cover. The actual values on incoming light during the summer correspond with a decrease of mean atmospheric transmission from 60 to 40% between 35 and 55° latitude.

Light is only partially correlated with latitude. Closeness to the sea is associated with more cloudiness. Further, there are more areas of high radiation in the southern than in the northern hemisphere (Black, 1956), and atmospheric transmission is often greater at higher altitudes.

The effects of light quality on tree behaviour are not yet well understood. Changes in the red:farred ratio are often accompanied by changes in light intensity. A reduction of the ratio between active and inactive forms of phytochrome is characteristic for dark parts of a canopy (Baldini and Rossi, 1987). This may enhance apical dominance, which could be a biological reaction of a plant at risk of becoming shaded (Casal and Smith, 1989). It may lead to strong vegetative growth at the expense of fruit-bud formation, which is unwanted in commercial orchards.

Water and nutrients

Nutrition is unlikely to exert a tree x orchard system interaction and rarely limits fruit production in commercial orchards. This does not hold for the availability of water, but, unfortunately, information on this topic is scanty. Competition for water may increase with decreasing spacing, which can lead to reduced growth or increased biennialism (Wertheim, 1985; Mitchell et al., 1989). Higher water use may be associated with a higher leaf-area index (LAI) or increased competition between grass and trees. The latter can occur when planting density increases at a constant width of grass alley but a narrower black strip beneath the trees (Atkinson, 1981). Differences in soil water deficit between tree densities may decrease or disappear in later years, when the canopy closes. Tree shape may exert an effect on transpiration, too. Horizontal or V-shaped canopies have a higher leaf exposure than vertical systems, and this leads to more transpiration and earlier water shortage (Jones et al., 1985). Furthermore, air turbulence and transpiration will be increased by gaps between trees. Lower transpiration rates may be expected in more sheltered systems.

Cultural factors

Light interception and leaf area

Maximum potential assimilation is realized by a canopy that absorbs all incoming light. Most studies have taken light interception into account instead of light absorption, thus ignoring canopy reflectance. This simplification can be justified, for the latter is generally small: about 0.06 for apple row crops with grass alleyways (Palmer and Jackson, 1977). Light interception depends on the spatial distribution of the leaves and LAI. The proportion of wood and fruit is much lower than that of the leaves (Palmer, 1988). Although leaf inclination varies with cultivar, many cultivars have a more or less planophile structure (Jackson, 1970; Cervenka, 1978; Rabbinge, 1976). Model calculations have predicted only a slight effect of leaf inclination on light transfer in mature orchards (Chapter 4). In orchards, maximum values for light interception and LAI are not desired. Human and machine access is needed for harvesting and cultural procedures. Furthermore, sufficient light penetration in deeper layers of the canopy is essential. The light saturation level for leaf photosynthesis is about 200 W m^{-2} for many apple and pear varieties (Kriedemann and Canterford, 1971; Proctor et al., 1976; Avery et al., 1979; Wagenmakers, 1990a). Although maximum irradiance is known to be twice as high over a wide range of the earth (Jones, 1983), most leaves will have to function at lower light levels due to low leaf transmittance. According to empirical data (Jackson, 1970; Cain, 1971), 30 and 50% of incident light should be transmitted to the interior canopy to satisfy the needs for fruit growth and economic fruit quality, respectively. This may generally hold for a range of latitudes if cloudiness is similar. The actual light requirements for a given cultivar may vary widely. Proctor et al. (1975) suggest that about 5 MJ of PAR m^{-2} day^{-1} should be received for red colour in 'McIntosh' apple trees. Other cultivars, such as 'Gloster', and in general, red mutants of various cultivars need less light for red-colour formation. Furthermore, less light may be needed with trees on dwarfing rootstocks than on vigorous ones (Proctor et al., 1975).

The need for adequate interior light penetration is further supported by the presence of spur leaves within the tree. This type of leaves is located close to a fruit and is relevant for fruit growth, particularly early in the season

(Hansen, 1967; Lakso, 1984; Lakso et al., 1989b). The relative contribution of spur leaves increases with tree ageing (Callesen, 1988).

For 51° N and half of the light being diffuse, maximum light interception is predicted to be between 70 and 80% at LAI values between 2 and 3 for a range of hedgerow spacings if 90% of the row is to receive more than 30% incoming light (Palmer, 1981). Similar values were found in experiments at the given latitude by Verheij and Verwer (1973), who measured yield loss at light interception exceeding 70%, and by Jackson (1978), who reported unacceptably low light levels at LAI values greater than 3. Occasionally, light interception and LAI may exceed these values without marked effects on yield. Light interception surpassing 80% at LAI values of 3.8 to 4.6 has been reported for well-cropping experimental full-field systems with 'Crispin'/M.27 (Palmer, 1988) and 'Elstar'/M.9 (Wagenmakers, 1990b). However, fruit colour may be poorer, particularly in the lower tree parts (Wagenmakers, 1990b).

To attain a given light interception, LAI in a given planting system should be higher at lower latitudes, where more direct light will strike the soil due to a higher solar elevation. Light interception on sunny summer days may differ by at least 5% for similar hedgerows at 50 and 30° latitude (Palmer, 1989b).

Conversion of light

According to Cooper (1975), C3-plants may convert at least 3% of the incoming light energy into dry matter. Genetic properties of rootstock and cultivar define the balance between vegetative growth and fruit production. Because dwarfing rootstocks provide modest growth and allocate many of their assimilates into fruit, they are characterized by a favourable harvest index (Avery, 1970; Fukuda et al., 1987). Maximum values for apple harvest index are 70%, higher values often being associated with biennial cropping patterns (Palmer, 1989a). The performance of rootstock-scion combinations varies widely in dependence on environmental and physiological conditions (Ferree and Carlson, 1987). Since the impact of the rootstock is primarily restricted to the scion, rootstock/scion x orchard system interactions are unlikely. Tree density may influence root distribution, but has little or no effect on the shoot:root ratio for trees on a given rootstock (Atkinson et al., 1976; Palmer, 1988). On these grounds, rootstock and cultivar comparisons are not considered here.

We may assume a productive cultivar on certain rootstocks that allocates 70% of its dry matter to fruit and a fruit dry-matter content of 15%. If 1 g dry matter is equivalent to 17.8 kJ incoming light (Cooper, 1975), then according to the incoming light represented in Figure 2.2, the potential change in fruit production would be 2.4 tonnes per ha per degree latitude. This fits in quite well with the value of 2.7 that is obtained when the empirically found conversion efficiency of 1.95 g total dry weight per MJ of PAR for apple (Palmer, 1989a) is used. In this approach, canopy photosynthesis and phenological differences, such as blooming date and leaf area development, are ignored. Canopy photosynthesis of a crop can be estimated on the basis of light absorption (Spitters et al., 1989). For simplicity, we may assume a homogeneous crop with a spherical leaf distribution, respiration costs to be 40% of gross photosynthesis and a five-month-long growing season in which final LAI is achieved after two months (Cain, 1973; Forshey et al., 1987). Further, it is assumed that the date of leafing out is proportional to latitude (Heim et al., 1979; Wagenmakers and Callesen, 1989).

Figure 2.3 illustrates the calculated fruit production as a function of latitude, cloud cover, and LAI. When atmospheric transmission amounts to 50% and LAI to 2.5, fruit yield is about the same at any latitude. Cloudiness and LAI have a marked effect on production. In general, the relationship appears to be non-linear, such that effects on production are greater with increasing latitude. When atmospheric transmission varies proportionally with latitude (according to Figure 2.2) and LAI is 2.5, the production level will be changed by up to 10%, and reduced by 27% when going from 35 to 55° latitude. Increasing LAI with lower latitudes will have an even greater effect on production than cloudiness will do. When LAI increases from 2.5 to 4.5 going from 55 to 35° latitude, and atmospheric transmission is 50%, the production will be changed by up to 33%, and the difference between the extreme latitudes will be 31%. The combination of variable cloudiness and LAI even results in an almost twice as high production level at the lowest latitude.

Potential production is also determined by the duration of the growing season. Calculation with the above-mentioned crop photosynthesis model shows that fruit production would be reduced by about half for a growing season lasting three months as compared to five months. Summer apples, therefore, will never reach the potential of later-season apples.

The results of calculation suggest that LAI may be more yield-limiting than cloudiness. However, the calculations do not account for leaf clustering. When trees are arranged in row systems, diffuse light interception is predicted to increase only slightly at LAIs greater than about 3 (Chapter 4). Besides, there may be negative shading effects on fruit yield and quality when

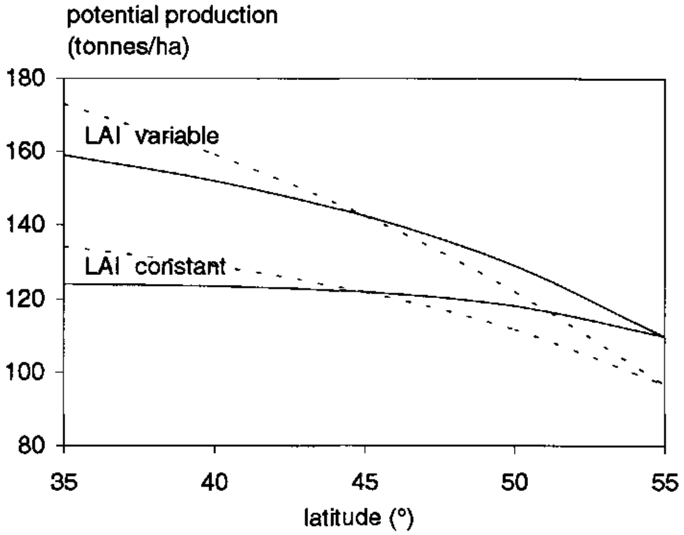


Figure 2.3

Potential fruit production as a function of latitude, fraction of atmospheric transmission (value is 0.5 (solid lines) or varying linearly from 0.6 to 0.4 between 35 and 55° (broken lines)) and orchard LAI (value is 2.5 or varying linearly from 4.5 to 2.5 between 35 and 55°).

LAI exceeds optimum values, so actual differences between latitudes due to LAI will probably be less extreme than indicated. If maximum LAI would be 3 and cloudiness would vary across latitudes, yield should roughly differ by 1.8 tonnes per ha per degree latitude. This calculated effect on crop photosynthesis is smaller than that based on conversion of incoming energy. In the first place this is explained by the non-linear photosynthetic light response. The combination of lower light intensities and longer daylength at higher latitudes leads to a relatively higher level of crop photosynthesis. Secondly, diffuse light is much more efficiently used by photosynthesizing leaves than the direct component is (Denholm and Connor, 1982; Marini and Barden, 1982b; Weiss and Norman, 1985). Measurements done for apple by Lakso and Musselman (1976) showed that the highest level of light penetration occurred when incident light was between 0.6 and 0.9 of that for clear skies; it should, however, be noted that sunflecks were avoided in this study.

Top yields as calculated above have occasionally been realized. Maximum values of about 180 tonnes per ha have been reported for New Zealand apple orchards, which was nearly 4 times average production (Wilton, 1989). Yields of about 100 tonnes per ha at 51° N have been attained with 'Golden Delicious' in full-field systems (Wagenmakers, 1989a) and in meadow orchards (Luckwill, 1978). Experimental Danish designs with unthinned and unpruned 'Spartan' and 'James Grieve' achieved ceiling levels of 80 and 90 tonnes per ha, respectively (Vittrup Christensen, 1979).

Tree density

LAI and light interception increase with tree density, particularly in the early years. Numerous field experiments have confirmed the positive relationship between yield, light interception, and tree density (Verheij and Verwer, 1972; Palmer and Jackson, 1977; Jackson, 1980; Wertheim et al., 1986; Hunter and Proctor, 1986; Palmer et al., 1989; Wagenmakers, 1989b; Wagenmakers and Callesen, 1989; Robinson and Lakso, 1991). Table 2.1 illustrates this for 'Elstar' apple trees in various arrangements. Provided good management, this relationship holds for mature orchards, too. An average increase from 30 to 45 tonnes per ha has been found for a range of mature commercial orchards with densities of 2000 and 4000 trees per ha (Cahn-Shaharudin and Goedegebure, 1991). Occasionally, little or no relationship between tree density and yield may be found (Vandenende and Chalmers, 1983; Wertheim, 1984; Mitchell et al., 1989; Wagenmakers, 1989a). This will occur earlier when vegetative growth becomes excessive. The increase in tree density may reduce the percentage of large and well-coloured fruit (Palmer and Wertheim, 1981). When adjusted for crop load, differences may become less significant (Robinson et al., 1991).

Table 2.1

Light interception, production, and percentage well-coloured fruit for 'Elstar' at Wilhelminadorp, The Netherlands, averaged for the 5th–8th growing season.

trees/ha	rectangularity	% light interception	production (tonnes/ha)	% well-coloured fruit
2000	1:1	53	38.3	87
	3:1	46	36.5	81
2667	1:1	60	42.6	87
	3:1	54	38.7	79
4000	1:1	75	50.8	81
	3:1	64	42.5	73

Dense systems with small trees have a higher maximum light interception than wider-spaced systems with large trees. Two-m tall row systems with a free alley 0.5 m wide are predicted to intercept as much light as 4-m tall palmette hedgerows with 2.5 m wide alleys with 50% less leaves, while the canopy volume receiving more than 30% light is almost doubled (Palmer, 1981). Canopy volume is therefore no accurate measure for potential production.

Planting system

Light interception increases and interior light distribution improves when the canopy approaches a continuous crop (Jackson, 1989b). For orchard systems, this can be approached by designs with lower degrees of rectangularity (ratio of between-to-within-row spacing). Such systems have a higher yield potential and a lower optimum tree density (Jackson, 1980; Grace, 1988). At the same LAI, calculations showed that square plantings (1:1 ratio) intercept up to 20% more light than 3:1-systems do for a range of densities between 3000 and 20,000 trees per ha (Wagenmakers, 1991a). This has been confirmed by the results of several field experiments. Full-field systems attained 10% higher yields at a 12% lower tree density than more rectangular single rows (Wertheim, 1985). Due to a more uniform light distribution, square plantings had better coloration of red fruit than 3:1 plantings, too. The effects of arrangement may increase with increasing densities, where rectangular arrangements appear to be more strongly affected by inter-tree competition (Table 2.1). The optimum tree density can be twice as low for square plantings as for 3:1 systems (Cripps et al., 1975). The advantage of lower rectangularity is often limited to a given range of densities (Cripps et al., 1975; Vittrup Christensen, 1979). With wider spacings, production capacity can be reduced by poorer light distribution within the canopy or by a less sheltered environment between the trees. The absence of a positive effect of rectangularity at narrower spacings can be due to increased light competition in trials where trees have received insufficient pruning.

Despite its advantages, square planting is rarely applied on a commercial scale. Such plantings need higher capital investment for equipment adapted for over-the-row spraying and transport at harvest, that may not compensate for higher yields particularly with small-scaled orchards. Therefore, as a compromise form, multi-row bed systems in which two or more tree rows are separated by alleyways, were invented. Access is supplied by walking paths lying at an oblique angle to the alleyway. Because these systems are less rectangular, they intercept more light and show less variation in light distribution across the row than single rows do at a given tree density and size.

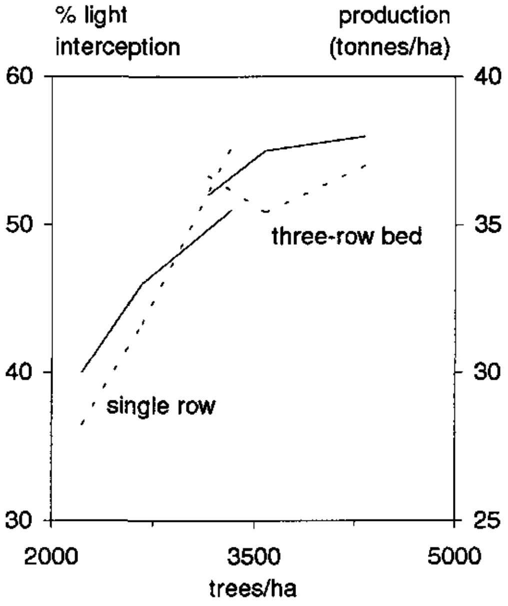


Figure 2.4

Diffuse light interception (solid lines) and mean apple production (broken lines) (first 4 cropping years) for single rows and three-row bed systems.

However, although higher production and fruit quality have occasionally been achieved with multi-row systems than with single rows (Vittrup Christensen, 1976), similar or lower yields from multi-row systems occur more often (Siegrist, 1984; Wertheim, 1984; Wertheim et al., 1986; Keppel, 1987; Wagenmakers, 1988; Rüger, 1989; Widmer et al., 1989; Scholtens, 1990). Figure 2.4 illustrates the effect of tree density and planting system on light interception and actual production of the first four cropping years for a 2-m high spindle tree with a width of 1.25 m. This tree can be arranged either free-standing, touching, or overlapping, and tree density may vary between 2200 and 3300 or 3150 and 4300 trees per ha for single rows and three-row beds, respectively. Although in both planting systems light interception and production per ha increase with planting density, the slope is less steep for the higher-density multi-row bed. This is explained by the higher degree of internal shading, reducing productivity, particularly in the inner rows (Chapter 4).

Since the input of chemical control is likely to be reduced in the future due to increased concerns about health and environment, alternatives for weed and growth control and crop protection are under investigation. Examples are mechanical weed control, growth control by mechanical root pruning, and the use of tunnel sprayers for the application of pesticides. These changes may influence the choice of the planting system. Current multi-row systems with walking paths not orientated parallel to the alleyway are complicated to mechanize. Single rows or multi-row systems with walking paths lying parallel to the alleyway might replace current multi-row beds, because they allow mechanization more easily. Integrated fruit growing need not mean reduction of tree density, because the lower LAI required in high-density plantings for optimum light utilization may reduce the amount of chemicals per ha required.

Row orientation

Row orientation influences both light and temperature patterns. Its effect is related to solar height and varies during the season, with latitude, and the fraction of direct light (Cain, 1972; Charles-Edwards and Thorpe, 1976; Palmer, 1989b). Orientation has more effect on light interception by tall hedgerows or systems with wide alleyways than it has on systems with small trees or narrow alleyways. Table 2.2 shows that N-S rows at higher latitudes intercept more (direct) light during the summer. This difference decreases when the season proceeds and finally E-W rows may intercept more light. At lower latitudes, this pattern is similar for narrow spacings and for wide spacings in the early part of the season. However, wide N-S rows may finally intercept more light than wide E-W rows. In general, N-S orientation is recommended because of the even light distribution on both sides of the row during the day. The fraction of well-illuminated canopy is on average about 10% lower for E-W rows (Palmer, 1989b). Very low light levels have been found on the shaded side of an E-W row against high light levels, but unfavourably high temperatures on the sunny side for a clear summer day (Baldini and Intrieri, 1987). The latter can lead to sunburn (Devyatov and Gorney, 1978). Significant decreases in flowering and production have been reported for E-W pear rows, in part due to greater frost damage to flowers on the shaded side (Lombard and Westwood, 1977). A slight tendency toward better fruit quality on the east side of N-S systems has been observed,

Table 2.2

Predicted light interception (% of incoming light) at two row spacings and latitudes under sunny conditions within hedgerows (2.5 m tall, 1.5 m thick at base, 0.5 thick at top) (from Palmer, 1989b).

		free alley width (m)			
		0.5		1.5	
latitude (°N)	orientation	21 June	21 Sept.	21 June	21 Sept.
51	N-S	73	79	56	62
	E-W	69	83	49	70
30	N-S	69	72	52	55
	E-W	62	75	44	53

relative to the west side, although there were no differences in light intensity and spur quality (Ferree, 1989). This might be explained by greater water stress in the afternoon on the west side.

Tree size and shape

Fruit trees are extremely variable in both size and shape, and tree geometry varies with pruning and training regime and genetic properties of the cultivar. Adequate tree management is indispensable for achievement of the desired geometry, but specific pruning and training effects will not be discussed here, because this topic has been covered elsewhere (Geisler and Ferree, 1984; Mika, 1986; Saure, 1987).

Generally, small trees show a greater proportion of well-illuminated leaves. At a given leaf density, large and small trees may have the same pattern of light penetration, but light levels will become lower deep in the larger trees (Proctor et al., 1975). Dwarf trees with a height of 2.5 m were found to have a greater LAI and still attained almost one-third more well-illuminated canopy than 6 m tall trees (Heinicke, 1964). The smaller tree has better light exposure due to the greater surface area per volume. This may lead to sunburn in certain areas (Barritt, 1991).

For opaque systems, maximum tree height can be calculated as a function of alley width and shape for a given latitude (Jackson and Palmer, 1972). Rectangularly shaped rows should be lower than triangular rows. Baldini and Intrieri (1987) predicted for northern Italy that a ratio of hedge height to row spacing greater than 1 was not optimal for the productivity of rectangular rows. Such ratios give an impression about the height of systems with extremely high leaf density. Trees are allowed to become taller when leaf density is reduced. At a given LAI, a single-row system with triangular spindles of 2 m high and 1.5 m wide free alleyways can intercept an equal amount of light as a system with rectangular palmettes of 4 m high and a free alley width of 2.5 m (Palmer, 1981). A lower leaf density probably explains the success of the 3 to 4 m high vertical axis, that produced 13% more than 2 to 2.5 m high slender spindles at the same tree density without loss of fruit quality (Wijsmuller and Wagenmakers, 1990).

Trees can roughly be subdivided in forms with rectangular and triangular sides. The former include many trellised systems, such as the vertical palmettes and cordons and the horizontal one- or multi-layered canopies (Lincoln, Ebro-espalier) (Tustin et al., 1989). Triangular tree shapes are represented by more or less free-standing trees such as central leader, vertical axis (Lespinasse and Delort, 1986), slender spindle, and trellised V-systems such as Tatura canopies (Chalmers et al., 1978). Many trellised systems have been developed for mechanical pruning and harvesting (Sansavini, 1975; Chalmers et al., 1978; Dunn and Stolp, 1981). Consequently, they require quite wide alleyways for machinery access. Other trellised systems, such as the European V-hedges for pear, were set up to reduce wind damage. V-hedges are also trained to reduce growth and stimulate fruiting, in particular with cultivars that grow not too vigorously (Reinhoudt, 1986). Many modifications of tree shapes have been developed for numerous reasons. The 'double spindle', where two branches on a leader are trained as a spindle, each being supported by a stake, has been introduced to reduce capital investment at planting (Evéquoz, 1988). The 'palmette leader', an intermediate between a palmette and a central leader, has been designed to improve light distribution of a central leader (Lakso et al., 1989a). The 'hybrid tree cone' has canopy volume of the vertical axis and the training system of the slender spindle, and should be applied at lower latitudes with a high amount of direct light (Barritt, 1991).

Trees with vertical sides and flat tops intercept more light than triangular trees of the same height and basal diameter. However, light distribution is poorer, because the top receives saturating light levels whereas the sides are under-illuminated. The alley width should be adjusted to the angle formed by the sides to the vertical, and should be narrower at greater angles to achieve adequate light interception (Cain, 1972; Jackson and Palmer, 1972).

A higher light interception and productivity of V-shaped canopies has been observed when compared to vertical systems (Robinson et al., 1991; Sugar and Buskirk, 1991; Wagenmakers, 1991a), although this is not general (Österreicher, 1989). Clayton-Greene (1989) compared eight methods of training apple trees in Australia including five trellised systems. All systems were planted at the same density and were pruned minimally. He did not find any significant difference in cumulative yield for the first four harvests, but found poorer colour on some trellised systems, probably due to poorer light penetration.

A more open training system in the absence of adequate pruning does not guarantee better light distribution or productivity. V-systems require regular summer pruning beside dormant pruning to keep the system open. Light penetration was reduced from 63 to 7% in pruned versus unpruned Lincoln canopies. This led to a reduction of apple fruit weight and yield from 179 to

116 g and from 47 to 32 tonnes per ha, respectively (Ferree et al., 1989). Comparable results have been obtained from multi-layered trellised canopies (Tustin et al., 1989). Elfving et al. (1990), comparing palmette-leader and central-leader trees that did not receive summer pruning, found only slight differences in light penetration. Probably leaf area was similar for both systems so leaf density was increased, impairing light penetration of the palmette leader.

Artificial manipulation of light

Reflective materials can be applied to increase the light intensity at deeper levels inside the canopy. Its positive effects on various aspects of yield and fruit quality have been reviewed by Palmer (1989a). Unfortunately, the reflective properties of most materials decrease rapidly with time (Mika, 1980). Further, results may be disappointing because in many mature systems only few light beams reach the ground. Currently, some growers apply black soil covers to reduce herbicide use. Preliminary field trials with similar covers of white colour have not shown higher yield or fruit quality, because the reflective properties were too small. The use of white supporting tree poles does not contribute to better light distribution in the canopy; their reflective area is too small, even in quite intensive systems (Wagenmakers, 1989c). Aikman (1989) suggested for greenhouses the use of partially reflective vertical screens between rows to increase the amount of diffuse light. The effects on photosynthesis will be greater at lower light intensities. Whether such techniques are feasible for field-grown fruit trees is therefore doubtful, apart from support problems.

2.4 Conclusions

Potential production of a given cultivar may change by about 2 tonnes per ha per degree latitude when accounting for daily light integrals and differences in cloudiness. Higher yields at lower latitudes will further be due to higher temperatures, offering the possibility of a longer growing season. The actual yield and fruit quality will however differ with cultivars. Intensive systems with high numbers of small trees per ha attain maximum yield earlier in the orchard's lifetime than extensive systems do. This is mainly due to a higher light interception and a higher proportion of well-illuminated canopy. The increase in production per ha is often associated with an increase in labour efficiency. The optimum tree density depends on rectangularity of spacing. At a given tree density, square arrangements attain higher production levels and fruit quality than rectangular plantings do. The optimum tree height is a function of the ratio between height and base of the tree, and the alley width, and should be greater as latitude and leaf density decrease. Horizontal trellised canopies have a higher yield potential than free-standing trees, but may suffer from too low light levels underneath the canopy, where the majority of the fruits are. V-shaped systems have a better potential performance if adequately pruned, and if the V-angle is adapted to the alley width.

3 Effect of latitude on potential apple production

Abstract

The effects of light and temperature on potential apple production were estimated by using a universal crop-growth model. Production was calculated for latitudes between 35 and 55°. The study was carried out for cultivars with different durations of growing season. The date of full bloom was assumed, on the basis of empirical data, to be related to latitude. Production was taken as a function of light absorption, gross photosynthesis and respiration by homogeneous canopies. The pattern of leaf development was assumed to be similar across latitudes.

The model calculations showed approximately the same production potential for early cultivars with a growing season of 4 months, for which a similar cloudiness, respiration, and LAI among latitudes was assumed. This was explained by the distribution of the growing season around the longest day. Cultivars with a late harvest date reached a higher production than early cultivars did, although this increase was very small for cultivars needing a growing season of more than 5–6 months at latitudes beyond 50°. More cloudiness at higher latitudes was responsible for up to 18% lower production, compared with the brighter conditions of the lowest latitude. When LAI was increased from 2 to 3.5, productivity was promoted by approximately 30%, but by only 10% at LAI between 3.5 and 5.

Due to higher costs of maintenance respiration, the production could be similar or, when LAI exceeded values of 3–4, even lower, at 35° compared with 45° latitude. At latitudes higher than 45°, production might also decline, because the reduction in gross photosynthesis would exceed that of respiration. On the basis of net photosynthesis, the maximum production for a cultivar with a 5-month growing season was calculated to occur at latitudes around 45°. The optimum latitude would be higher for cultivars with a shorter growing season.

For validation, model results were compared with normative apple production in Europe. The agreement was satisfactory, but actual yields in some northern regions were higher than expected. The latter could be due to in-

tensive crop management resulting in a higher light use. Actual yields were considerably lower than potential, indicating that other factors such as orchard management can be improved. With slight modifications, this model approach can also be used for other crops. To improve the estimation of production, more attention should be paid to respiration losses during the season.

3.1 Introduction

Apples originate from the Caucasian area, 41–44° northern latitude, but are now commercially grown in regions between 30 and 60° latitude, as well as at lower latitudes with higher altitudes. Absence of the required winter chilling leads to inadequate budbreak in subtropical climates, whereas low temperatures reduce the length of the growing season at high latitudes. The potential production is defined by radiation, temperature, and crop characteristics. These factors can give rise to considerable differences in productivity between latitudes, even for the same cultivar. Variation in actual production can be due to suboptimal orchard management, such as planting density and the shape and arrangement of trees, limiting factors such as water and nutrition, or reduction by weeds, pests, or disease. The present study aimed at a quantification of potential fruit production in relation to radiation and evaluation of the effect of temperature on respiration for cultivars with different durations of growing season and at different latitudes. Effects of orchard management have been reviewed elsewhere (Wagenmakers, 1991b).

Incoming radiation increases with decreasing latitude, which can lead to higher productivity, although the non-linear response of photosynthesis to light may cause a non-proportional increase. Mean temperature, too, increases with decreasing latitude. This leads to differences in phenological development. The growing season starts earlier at lower latitudes for a given cultivar. The time between bloom and harvest seems to be rather constant across latitudes (Kronenberg, 1989). To reach maturity, summer cultivars take 3–4 months after full bloom, whereas autumn cultivars may even need 7 months.

Orchard leaf-area index (LAI) values are found in a range between 2 and 5 and depend on orchard factors, such as planting density and cultivar, as well as tree management. Besides, high leaf areas are more common at lower latitudes (Heim et al., 1979; Palmer et al., 1989; Wagenmakers and Callesen, 1989; Palmer et al., 1992), which may lead to higher production at lower latitudes, unless excessive shading reduces fruit growth and flower-bud formation.

Lower latitudes will have higher costs for maintenance respiration. For apple, Q_{10} values of 2 have been reported (Butler and Landsberg, 1981; Ebert, 1991). Maintenance respiration is a substantial component of total respiration for trees. Buwalda (1991) showed for vines of kiwifruit that costs for maintenance during the growing season were about twice as high as those needed for growth. Even higher values have been found for roots of apple (Buwalda et al., 1992). These higher maintenance costs may reduce net production at lower latitudes.

3.2 Methods

Radiation and gross photosynthesis

Daily canopy assimilation is calculated from light absorption and the photosynthesis-light response curve of individual leaves, according to a general model developed for growth of agricultural crops (Spitters et al., 1989). The instantaneous radiation flux is derived from mean daily radiation data. The patterns of diffuse and direct light fluxes through the canopy are considered separately. Light absorption by the canopy follows an exponential pattern. Photosynthesis is integrated over different layers of the canopy and times of the day at a daily interval between the start of leaf development and harvest. Maximum gross photosynthesis, reached at light saturation, and light use efficiency were put at 0.972 mg CO_2 m^{-2} leaf s^{-1} and 0.0125 mg CO_2 J^{-1}, respectively. These values have been reported for apple (Avery, 1977), and generally represent the maximum for C3 crops (Goudriaan et al., 1985).

Data on the relationship between radiation and latitude are derived from weather files for 14 locations, considering a mean duration of the growing season of 5 months between bloom and harvest (Table 3.1). Atmospheric transmission (relative brightness of sky) was calculated from daily radiation according to Spitters et al. (1986). The mean seasonal value for atmospheric transmission was used to calculate daily radiation and the partitioning between direct and diffuse radiation at a given latitude (Spitters et al., 1986). On the basis of a linear regression on the data of Table 3.1, the incident global radiation and percentage atmospheric transmission are found to decrease by 0.079 GJ m^{-2} d^{-1}, and 0.73 per degree latitude, respectively. Mean seasonal values of atmospheric transmission are 0.35 and 0.50 for 55

Table 3.1

Weather-station observations on incoming global radiation and mean fraction of atmospheric transmission during a 5-month growing season. Data from O. Callesen, J.W. Palmer, S. Nonhebel (1991, pers. commun.), Royal Dutch Meteorological Institute, and CABO-DLO weather data system, The Netherlands.

latitude (°)	location	year	radiation (GJ m^{-2})	mean atmospheric transmission
38	Davis, California	(*)	4.13	0.57
41	Riwaka, New Zealand	(*)	3.20	0.45
41	Madrid, Spain	1987	3.29	0.46
42	Ithaca, New York	1987	2.73	0.39
43	Lincoln, New Zealand	1986	3.18	0.45
43	"	1987	2.67	0.38
44	Avignon, France	1971	3.23	0.47
49	Nancy, France	1980	2.31	0.35
51	Wilhelminadorp, Neth.	1986	2.88	0.42
51	"	1987	2.30	0.36
51	"	1988	2.30	0.35
51	"	1989	2.53	0.39
52	Wageningen, Neth.	1987	1.93	0.32
53	Bremen, Germany	1980	2.23	0.36
55	Roskilde, Denmark	1988	2.36	0.39
55	Aarslev, Denmark	1987	2.13	0.38
57	Silstrup, Denmark	1990	2.37	0.39
60	Bergen, Norway	1971	1.74	0.31

(*) long-term average data

and 35° latitude, respectively. Production is calculated between these extremes.

Phenology

The duration of leaf development varies with cultivar, rootstock and crop load. However, a general sigmoidal pattern of leaf development is mentioned in many reports (Avery, 1969; Barritt et al., 1991; Schechter et al., 1991) and agrees with accumulated growing degree-days (Johnson and Lakso, 1985). In the model, a forcing function for leaf growth and crop development was used instead of dynamic simulation of the growth of different plant parts. According to mean values of empirical data, leaf growth was assumed to start 2 weeks before full bloom and to reach maximum leaf area 2 months after full bloom. The most rapid growth occurred in the first 3 weeks after bloom

(Figure 3.1a). Calculations were done for LAI values between 2 and 5, following common orchard values.

Early, mid-season, and late cultivars were distinguished, with a growing season of 130, 165, and 215 days between start of leaf development and harvest, respectively. Time of full bloom usually ranges between 1.6 and 3.2 days per degree latitude (Landsberg, 1974; Heim et al., 1979; Kronenberg, 1989; Wagenmakers and Callesen, 1989; J. Grauslund, pers. commun., 1992). The mean value of 2.4 days earlier bloom per degree lower latitude was taken in the model. The assumed dates of full bloom and harvest per latitude are shown in Table 3.2.

Table 3.2

Simulated date of full bloom and harvest for an early, a mid-season, and a late cultivar (northern hemisphere).

latitude	full bloom	harvest		
(°N)		early	mid-season	late
35	25-3	18-7	24- 8	11-10
40	6-4	30-7	5- 9	23-10
45	18-4	11-8	17- 9	4-11
50	30-4	23-8	29- 9	16-11
55	12-5	4-9	11-10	28-11

Dry-matter distribution

The pattern of assimilate allocation to various tree components is influenced by the sink strength of the individual growing components. Generally, fruits are strong sinks and compete with wood and roots, but the functional relationships during the season have not been taken into account. Dry-matter distribution may vary with light levels within the canopy. At low light levels, flower-bud formation and fruit growth can be reduced (Palmer, 1989a). This interaction has not been taken into in this analysis, because of lack of empirical data. Instead, we applied a fixed function of dry-matter distribution, using mean annual values provided by Verheij (1972), Heim et al. (1979), Palmer (1986, 1988), J.A. Kipp (pers. commun., 1991), de Gendt (1993) and Wagenmakers (1993) (Table 3.3). Total carbon biomass was derived from LAI, using an average value of specific leaf weight of 128 g m^{-2} (personal data).

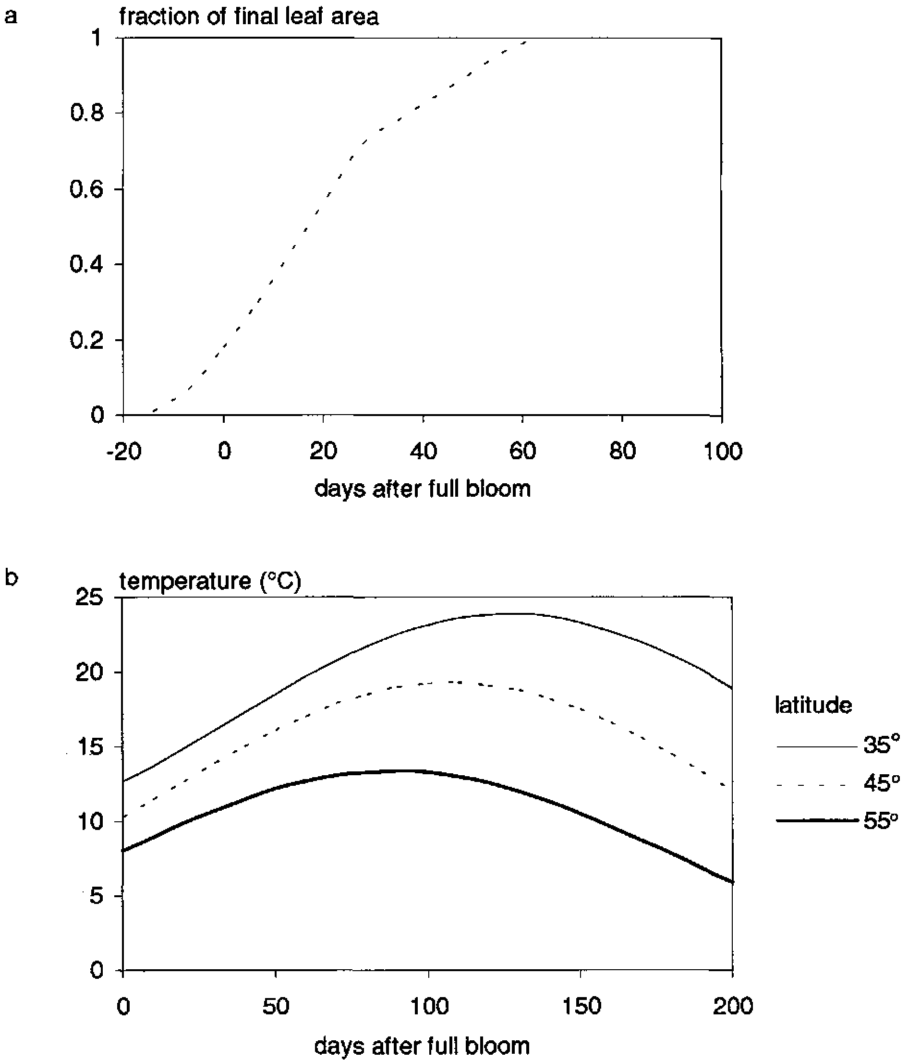


Figure 3.1

a. Simulated leaf area between full bloom and harvest.
b. Mean daily temperature between full bloom and harvest (from Charles-Edwards, 1982).

Table 3.3

Annual dry weight distribution in fruiting apple trees

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	mean
fruits	61	59	66	56	54	65	55	59
leaves	14	13	12	18	15	23	14	16
frame (incl. roots)	25	28	22	25	31	12	31	25

(1) 'Jonagold'/M.9, year 2 (J.A. Kipp, pers. commun., 1991)
(2) 'Jonagold'/M.27, year 3 (de Gendt, 1993)
(3) 'Golden Delicious'/MM.106, year 3 (Heim et al., 1979)
(4) 'Golden Delicious'/M.9, year 4–5 (Palmer, 1986)
(5) 'Golden Delicious'/M.9, year 5 (Verheij, 1972)
(6) 'Crispin'/M.27, year 3–5 (Palmer, 1988)
(7) 'Elstar'/M.9, year 2–10 (Wagenmakers, 1993)

Gross and net photosynthesis

Gross photosynthesis and respiration were calculated for 130, 165, and 215 days after leaf emergence. Daily net photosynthesis was expressed as

$$P_{net} = P_{gross}\, Y_g - R_m$$

where Y_g is growth efficiency and R_m denotes maintenance respiration. The organ-specific parameters for the above-ground parts were derived from empirical data published by Butler and Landsberg (1981). The specific respiration rates, expressed in mg CO_2 s^{-1} m^{-2} orchard area, were estimated as

$$r_f = n\, a_f\, 4\, \pi\, r^2\, e^{(k\,T)}$$

$$r_w = a_w\, m_w\, e^{(k\,T)}$$

$$r_l = a_l\, LAI\, e^{(k\,T)}$$

where the subscripts f, w and l denote fruit, wood and leaves, and a is an organ-specific constant, being 0.01, 0.0028, and 0.003 for fruit, wood, and leaves, respectively (mg CO_2 s^{-1} m^{-2} fruit surface, mg CO_2 s^{-1} g^{-1} dry wood, and mg CO_2 s^{-1} m^{-2} leaf area), m is dry weight (g m^{-2} orchard area), n is fruit number (m^{-2} orchard area), r is fruit radius (m), T is mean daily temperature (degrees Celsius), and k is a respiration coefficient, amounting to 0.084 for all organs. According to Butler and Landsberg (1981), seasonal changes in respiratory coefficients are small, except for short periods early in the season, and therefore were not taken into account.

Root respiration (μmol CO_2 h^{-1} m^{-2} orchard area) is derived from

$$r_r = m_r\,(0.41\ T - 0.11)$$

where the subscript r refers to roots (Ebert, 1991).

Mean daily temperature was calculated on the basis of a sinusoidal function between temperature and time in the year, using the equations given by Charles-Edwards (1982) as illustrated in Figure 3.1b. The differences in mean daily temperature increase from less than 0.5°C at bloom to more than 1°C per degree latitude at harvest.

Growth respiration depends on the chemical structure of organs and is not influenced by temperature (Penning de Vries and van Laar, 1982). Based on the relative composition of carbohydrate, protein, fat, lignin, organic acid, and minerals in the individual organs, calculation shows that 1 kg dry weight of fruit, leaves, and woody tissue (including roots) corresponds to 0.17, 0.33, and 0.32 kg CO_2, respectively (Penning de Vries and van Laar, 1982). Since carbohydrates are the main components of fruits, their synthesis costs are lower than those for leaves or wood, which have higher levels of protein and lignin, respectively. Calculation with the dry-matter distribution data in Table 3.3 shows that approximately 16% of the seasonal carbohydrate production would be needed for growth.

3.3 Results

To allow expression of the relative effects of the various factors, the results for seasonal production are presented as percentages rather than as absolute values, unless otherwise stated. The value of 100% is assigned to latitude 35°, LAI 5, and normal cloud cover for the given latitude.

Effect of radiation

If LAI and atmospheric transmission were similar at all sites, the potential production would change only slightly with latitude for early cultivars. For cultivars needing a longer growing season the production level will be higher, an effect which is more pronounced at lower latitudes (Figure 3.2a). There is a strong relationship between incoming radiation and production. The highest production will be found where the growing season is evenly distributed around the longest day, which occurs at latitude 50° for an early cultivar (Table 3.2). This light distribution pattern is less favourable for later cultivars at higher latitudes, which have an increasing part of their growing season beyond the longest day.

Figure 3.2b shows the effect of atmospheric transmission on production. Extremes are set at 0.35 and 0.5, which are the mean seasonal values of actual fractions for latitudes 55 and 35°, respectively (Table 3.1). The 'normal' values are assumed to be a linear function with latitude between these extremes. 'Normal' differences in cloudiness between latitudes can be responsible for considerably lower production. The production of an early and a late cultivar at 55° falls from 40 to 33% and from 55 to 45%, respectively, assuming a fraction of atmospheric transmission of 0.50 and 0.35. A decrease of 3–18% production can be due to the greater cloudiness at latitudes 40–55°. Although values of atmospheric transmission higher than 0.5 are not unusual on a daily basis, production will increase only slightly (Table 3.4). The results are presented at an LAI value of 2, but patterns for higher LAI values are similar (data not shown).

Figure 3.2c gives an example of the effect of LAI, given the same cloudiness for all latitudes. Production can be increased by one-third when the LAI increases from 2 to 3.5. A further increase of LAI from 3.5 to 5 will lead to only 10% more production. It can be expected that lower latitudes benefit slightly

Table 3.4

Dry-matter production (% of maximum value per latitude) at three different latitudes, LAI 2, and a range of atmospheric transmission values for a mid-season cultivar.

atmospheric transmission	production at latitude		
	35°	45°	55°
0.1	31.0	29.9	28.1
0.2	54.6	53.2	50.5
0.3	72.6	71.3	68.8
0.4	85.9	85.0	83.2
0.5	94.8	94.3	93.1
0.6	99.5	99.2	98.5
0.7	100.0	100.0	100.0

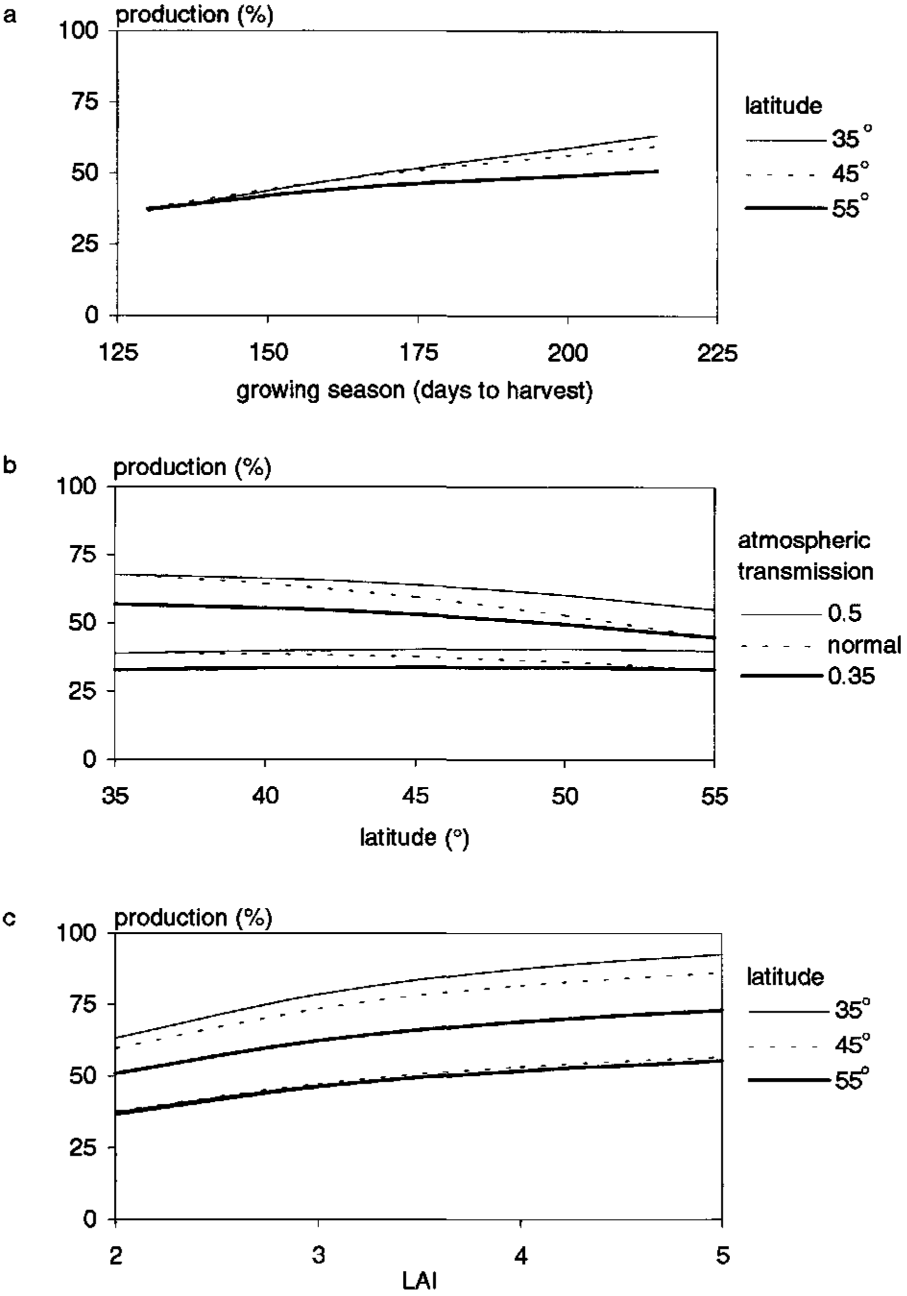


Figure 3.2 (see next page)

Figure 3.2 (opposite page)

Effect of radiation and of

a. duration of growing season, assuming similar cloudiness and LAI across latitudes;
b. three values of atmospheric transmission, under the assumption of similar LAI, for an early (lower curves) and a late (upper curves) cultivar;
c. three values of LAI for an early (lower curves) and a late (upper curves) cultivar, under the assumption of normal cloudiness per latitude.

more from a larger LAI than higher latitudes would. Similarly, the effect of LAI will be slightly more important for early than for late cultivars. This is related to the interception of direct light beams, which is less efficient at a higher solar inclination. This effect is, however, very limited.

Table 3.5 illustrates the effect of a combination of higher LAI and less cloudiness at lower latitudes. When LAI is assumed to be a linear function of latitude, varying between 5 and 2 going from latitude 35 to 55°, and atmospheric transmission follows the normal pattern across latitudes (see above), the maximum production occurs at latitude 35° and LAI 5, where early cultivars reach approximately the same production as mid-season cultivars at latitude 45° and LAI 3.5. The differences between latitudes are even larger for cultivars with a longer growing season. Under the given conditions, none of the cultivars at latitude 55° and LAI 2 will reach values similar to those achieved by any cultivar at a lower latitude. However, with LAI 3.5, slightly more production is achieved by early and mid-season cultivars than at lati-

Table 3.5

Effect of radiation on production (%) under the assumption of normal cloudiness and similar respiration per latitude.

cultivar	LAI	35°	45°	55°
early	2.0	39.3	37.5	33.0
	3.5	53.3	50.4	42.5
	5.0	59.5	56.5	47.5
mid-season	2.0	51.9	47.6	39.9
	3.5	69.7	64.1	50.0
	5.0	78.0	70.4	55.5
late	2.0	67.0	57.7	44.9
	3.5	88.9	77.7	55.2
	5.0	100.0	83.7	61.0

tude 45° and LAI 2. Late cultivars at 35 and 45° latitude still produce considerably more than earlier cultivars do, but the difference relative to mid-season cultivars is only slight at 55°, which may be ascribed to very low light levels in the end of the year.

Effect of temperature and respiration

Figure 3.3 illustrates the maintenance costs of the various tree components per latitude on a day 5 months after full bloom. Patterns for the other dates (4 and 7 months after full bloom) show the same tendencies. For the given pattern of carbon allocation (Table 3.3), fruits and leaves will account for the majority of maintenance costs, but roots, too, share a significant proportion of respiration, despite their relatively low biomass. Perennial above-ground structures (trunk, branches, and shoots) account for not more than 5% of maintenance. Leaves and roots have the highest costs per unit of weight. The carbon losses from maintenance decrease non-linearly with increasing latitude.

At harvest date of an early cultivar, maintenance respiration (R_m) can amount to 35% of gross photosynthesis, averaged over latitudes (Table 3.6a), assuming total dry weight to be the same. This percentage is roughly

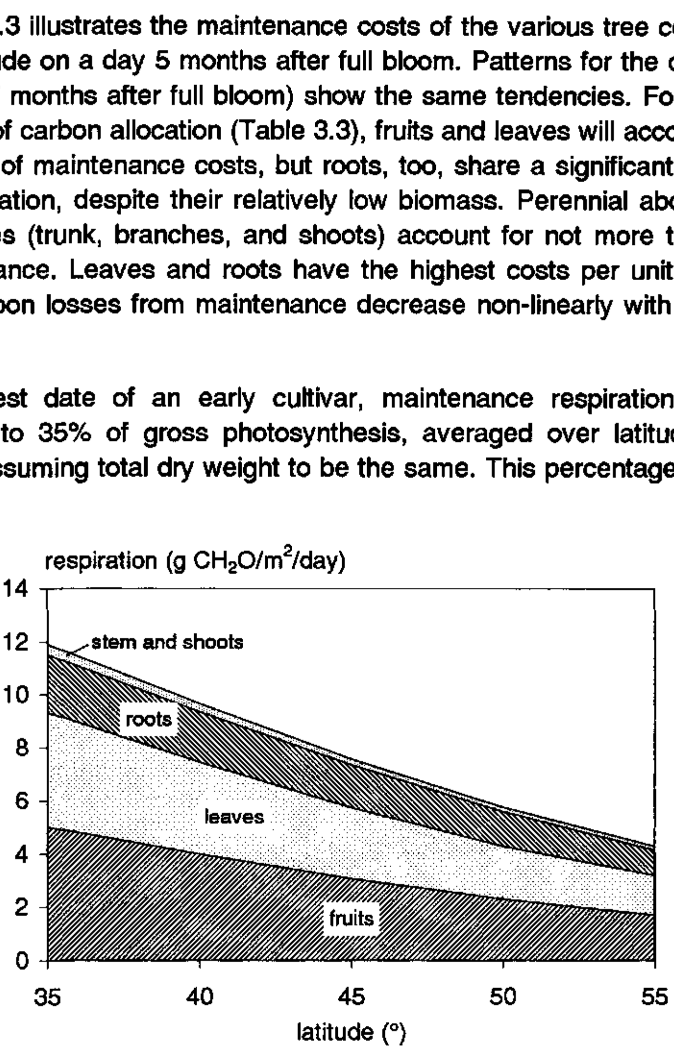


Figure 3.3

Cumulative maintenance respiration per unit soil area and latitude, under assumption of similar biomass across latitudes. Illustrated for a mid-season harvest day.

the same later in the season and at lower latitudes, but increases markedly at latitudes beyond 45°. At latitude 50° a disproportional increase in the percentage of R_m is found, which is even more pronounced at 55°. This is due to a decline in gross photosynthesis. Because of relatively high maintenance demands, net production will be almost similar at 35 and 45° latitude between 4 and 5.5 months after flowering, but lower gross photosynthesis leads to less net production at a higher latitude. Later in the season, however, this reduction of gross photosynthesis may induce an almost linear decrease of net production with increasing latitude (Figure 3.4a).

Table 3.6

Calculated values for R_m (% gross photosynthesis) at harvest date (early, mid-season, and late), assuming LAI 2 at all latitudes (a) or LAI increasing from 2 to 5 going from latitude 55 to 35° (b).

latitude	early		mid-season		late	
(°)	(a)	(b)	(a)	(b)	(a)	(b)
35	42	74	44	77	40	74
40	38	59	40	63	38	62
45	34	46	36	51	38	55
50	31	36	35	43	42	52
55	28	28	37	37	57	57

The proportion of R_m per latitude will be lower as dry mass decreases with increasing latitude. If LAI decreased linearly from 5 to 2, average maintenance costs at an early and a mid-season harvest date would decrease from 75% to 33%, going from latitude 35 to 55° (Table 3.6b). At a late harvest date, the lowest proportion of Rm would occur at latitudes 40–45°. As Figure 3.4b shows, maximum daily net photosynthesis is found at latitude 45–50° for an early harvest date, under the assumption of more dry mass at lower latitudes. This value shifts to latitude 40–45° at mid-season, whereas latitude 40° is associated with the highest net production 7 months after bloom. The results show that early cultivars can be expected to have the highest net production at the intermediate latitudes, whereas later cultivars produce maximally at lower latitudes. Under these conditions, the highest production cannot be reached at 35° latitude, despite the highest input of radiation.

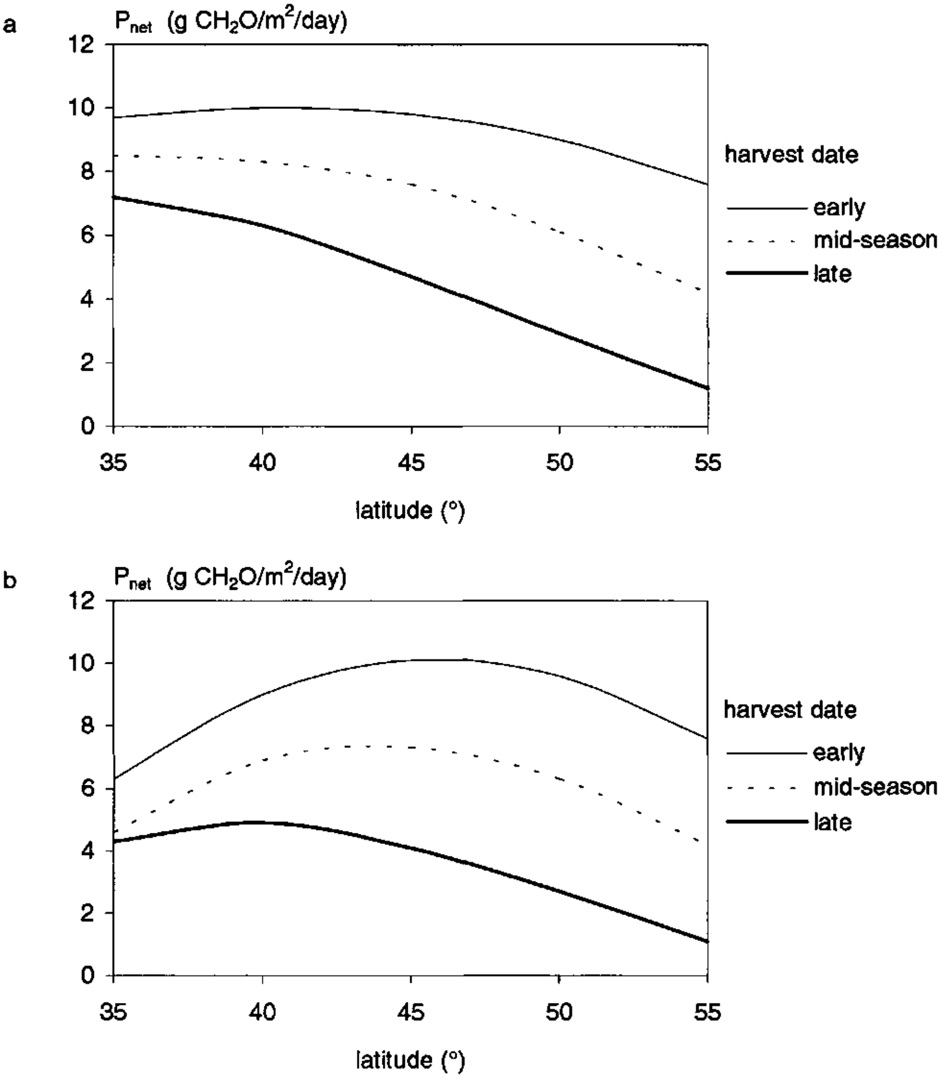


Figure 3.4

Effect of radiation and temperature on different dates and normal cloudiness per latitude, under the assumption of:

a. similar LAI across latitudes;
b. higher LAI at lower latitudes.

3.4 Discussion

Radiation

According to radiation, significant differences in potential production can be expected between latitudes in a range of 35–55° and between cultivars with differing duration of growing season. In general, there is a strong proportionality between radiation and production. Lower latitudes benefit slightly less and higher latitudes slightly more from higher levels of radiation, due to the non-linearity of the photosynthesis-light response curve. The highest dry-matter production for a given cultivar is found when the growing season is evenly distributed around the longest day. This condition is satisfied rather similarly between latitudes for early cultivars, ripening about 4 months after bloom. They can have almost similar production levels across latitudes, given the same LAI (Figure 3.2c). As the duration of the required growing season increases for cultivars ripening later, the differences between latitudes increase and the region with maximum production potential will shift towards lower latitudes. Mid-season cultivars needing a growing season of 5–6 months may have a production up to 30% higher than that of summer cultivars, which is attributed to a longer period of radiation interception. At low latitudes, late cultivars may produce even 80% more than summer cultivars do. Such a benefit of later cultivars is, however, very limited at latitudes beyond 50°, because of a sharp decrease in radiation input with increasing latitude at the end of the season.

If day-to-day variation of radiation is not taken into account, simulated production can be overestimated by 10%, which is attributed to the non-linear relationship between light and photosynthesis (Nonhebel, 1993). Mean seasonal atmospheric transmission was used to calculate daily radiation. With this simplification, seasonal incident radiation was underestimated by 15%. This is due to the non-linear relationship between atmospheric transmission and the partitioning between direct and diffuse radiation (Spitters et al., 1986). Calculation showed that dry-matter production based on the mean value for atmospheric transmission was 99% of that based on daily values for the group of weather stations listed in Table 3.1. Obviously, the 15% deviation is compensated for in some way by the non-linear photosynthesis response to light. Photosynthesis increases with atmospheric transmission values up to about 0.5, but changes only slightly at higher values (Table 3.4).

Respiration

When maintenance costs are taken into consideration, productivity is reduced at lower latitudes. This effect will be most pronounced in the second half of the growing season, because of larger differences in temperature between latitudes (Charles-Edwards, 1982) and a larger biomass. The calculated mean values of maintenance respiration in this period (40–50%) fell within the range found for other crops (Amthor, 1989), and are lower than those for forest communities (Kira, 1975), where the share taken by vegetative perennial tissues is greater. Lower values (25%) for apple at Bonn (latitude 51°) during the summer were also reported by Wibbe et al. (1993). Root respiration was, however, not measured in this experiment. According to our results, this might increase respiration to approximately 30%, a value that fits in with calculated R_m at the given latitude.

Calculated R_m in the second half of the growing season varied between 30% and 80% of gross photosynthesis (Table 3.6), the highest values being found at lower latitudes for canopies with a high value for biomass. Since differences in temperature between latitudes are smaller and biomass is also smaller early in the season, these values should be regarded as a maximum. Because gross photosynthesis, unlike maintenance costs, does not increase much above LAI 3–4, this might be the optimum LAI for net production. Buwalda (1991) reached the same conclusion for kiwifruit. Even if total biomass were similar, higher respiration costs could eliminate the benefit of greater gross production. This would lead to approximately the same net production between latitudes 35 and 45°. Higher latitudes may be associated with lower production. If lower latitudes were associated with more growth and total biomass, the highest net production might be found at even higher latitudes (45–50°). Such a reduction of net productivity due to respiratory losses probably explains why certain forest trees growing in the warm-temperate zone and the boreal zone reached a similar production level (Kira, 1975). Our results show that higher latitudes may benefit from lower R_m until about 5 months after bloom. Later, the reduction of gross photosynthesis surpasses that of Rm, resulting in a lower net productivity.

Leaves and roots account for a large share of respiration. Theoretically, their contribution can be reduced by tree management such as training or rootstock choice. To guarantee a regular perennial production pattern, however, an optimal amount of carbohydrates going into the fruit should be found, instead of the maximum possible amount. There is empirical evidence that this amount should not exceed 70% (Palmer, 1986). For various cultivars and rootstocks, the minimum proportion distributed to the leaves seems to be quite constant and amounts to 15–20% (D.J. Avery, 1991, pers. commun., Table 3.3). If 70% and 15–20% are assumed to be allocated to fruit and leaves, respectively, the minimal percentage for woody tissue would be 10–15%. Thus, the amount of wood probably cannot be reduced further than the value used in the present calculations.

The level of fruit respiration varies with cultivar. Our calculations were based on data for 'Golden Delicious' published by Butler and Landsberg (1981), a cultivar that is known to have a very efficient internal CO_2-refixation. Higher respiration costs are known for other cultivars such as 'Cox's Orange Pippin' (Blanke, 1988). Early in the season, fruit photosynthesis may slightly reduce these costs (Blanke and Lenz, 1988). Woody tissue (excluding roots) contributes less than 5% to total respiration, according to the present calculations, and seems of minor importance, which has been confirmed by experiments (Cordes, 1988).

The present study was restricted to the period between bloom and harvest. However, carbohydrates are also produced and consumed in the period between harvest and bloom. So far, the model has not taken reserves into account. At lower latitudes more reserves can be stored, because of better light conditions between harvest and leaf drop (Priestley, 1963), and a longer period of leaf activity. On the other hand, higher winter temperatures may lead to greater carbohydrate losses. The importance of reserves with respect to new growth has been questioned (Priestley, 1981).

Potential and actual production

For a canopy with 60% of the carbon going into the fruits, 50% maintenance costs and the given photosynthetic characteristics (see used methods), fresh fruit yield (fruit dry weight 15%) for an early, a mid-season, and a late cultivar would be approximately 80, 110, and 150 tonnes per ha, respectively. These values would be reached at 35° latitude, under the assumption of normal cloudiness and LAI of at least 3.5. The lowest values would be found at the highest latitude and LAI of 2, where production was estimated at 50, 63, and 71 tonnes per ha for the various cultivars, respectively. Their yields could theoretically be increased to approximately 80, 100, and 115 tonnes per ha when LAI should be at least 3.5. Although such yields are not unknown, particularly for the mid-season and later cultivars, actual values are generally lower, which indicates that the growing conditions can still be substantially improved. A good example of high production potential is the situation in New Zealand, where top yields of 180 tonnes per ha have been reported. This is approximately twice as high as top yields in The Netherlands (Wagenmakers, 1991b). At Riwaka (New Zealand, 41° S), radiation is normal for the given latitude (Table 3.1), but the mean temperature during the growing season lies between 10 and 17°C, which corresponds with values of a 10° higher latitude (J.W. Palmer, 1991, pers. commun.). Assuming a final LAI of 4, calculation showed that net production of early, mid-season, and late cultivars would be 15, 19, and 23% higher than that at standard temperature, respectively.

Actual differences in fruit yield between cultivars may be larger than predicted due to a variable dry-matter distribution. The pattern of allocation appears to be determined almost entirely by crop load and not by latitude (Heim et al., 1979). The percentage of assimilates going to the fruit we used was 59, but particularly summer cultivars may not be able to reach this high value. Maximum values of 'Summerred' apple on M.9 rootstock were less than 50% (de Gendt, 1992), probably because ripening occurred before maximum fruit weight was reached. Our calculations do not account for reduced metabolic activity due to water shortage, affecting both photosynthesis and respiration (Blanke and Lenz, 1988; Amthor, 1989). Although water shortage is more likely to occur at lower latitudes, actual reduction of net production may be smaller, since trees can adapt to the climate on the long term (Penning de Vries, 1975).

The effect of temperature on photosynthesis has not been taken into account. Wibbe (1991) reported a linear relationship between temperature and photosynthesis. This would further increase the production potential at lower latitudes. The optimum temperature for apple growing lies between 18 and 25° C (Huang, 1990), a range which is usually found at latitudes below 45°. However, the optimum for individual cultivars can differ significantly, which is reflected in the preference of cultivars for certain climates. This does not rule out that some general cultivars are grown over a wide range of latitudes.

For a general cultivar with a growing season of at least five months, calculation showed that maximum net production may occur around latitude 45°. Normative yields per ha are illustrated in Table 3.7 for some cultivars. The high fruit yields reported for northern Italy and southern France (latitude 44–46°) and the lower yields at lower latitudes (Spain, Greece, Portugal, 39–42°) and higher latitudes (northern Germany and Denmark, 54–55°) cannot be explained by radiation alone, but confirm the model's calculations for respiration. However, in The Netherlands and Belgium (latitude 50–52°), actual yields were only slightly lower than those in Italy or France

(Goedegebure et al., 1991). A comparative study with pear showed similar trends (Goedegebure et al., 1994). According to our calculations, higher respiration costs in the southern regions could be responsible for lower yields, but orchard management is also important. Intensification of the planting density, including higher LAI, was highest in The Netherlands and Belgium and could have partly compensated for lower potential yield due to less radiation.

Table 3.7

Normative apple yield (tonnes per ha) in Europe for a full-grown orchard with more than 1600 trees per ha (from Goedegebure et al., 1991).

	latitude (°)	'Golden Delicious'	'Jonagold'	'Elstar'
Greece	39	23.2		
Portugal	41	18.4		
N. Spain	42	32.0		
S. France	44	45.3	44.1	
N. Italy	45	45.3	44.1	41.9
S. Germany	48	39.0	38.0	36.0
Central Germany	49	36.8	35.9	34.1
Belgium	50	42.0	42.0	37.0
Netherlands	52	40.0	39.0	37.0
N. Germany	54	33.7	32.8	31.2
Denmark	55	26.3		24.3

The current calculations show the causes of differences in potential productivity across latitudes. As such, crop-growth models offer a tool to increase understanding of the process that determines an optimum climate for fruit growth and the possibilities per region. This model can further be used to estimate consequences of climate changes for apple growing. With slight modifications, the model is also applicable to other fruit crops. Some aspects can be refined. The concept of leaf development at different latitudes can be improved. The problem of estimating partitioning is central to the quantification of the carbon needs for growth and maintenance of the various tree organs and tissues during the season. Extension of the model by linking the relationship between light interception and canopy geometry (such as tree density, shape, arrangement) would also improve the estimation of actual production.

4 Simulation of light distribution in dense orchard systems

Abstract

A model for the assessment of light transfer through orchard systems is described. Tree shape is approximated as conic, parabolic, cylindrical or as intermediate between a cone and a cylinder. Trees may vary in dimensions. The foliage is assumed to be black and uniformly distributed throughout the crown. Any number of similarly shaped trees can be positioned in any desired arrangement. The model incorporates three dimensions and distinguishes between direct and diffuse components of light.

The agreement between calculated and measured interception and distribution of light was generally good for spindle-type apple and pear orchards. Discrepancies may arise from incorrect assumptions concerning tree parameters such as tree size and leaf area. The relative importance of tree density, spacing, and shape is discussed. It was found that multi-row systems, in which two or more rows of trees are separated by alleyways, may have a greater light interception than single rows do. However, the model suggested that poorer light distribution is associated with multiple rows, particularly where tree crowns overlap. Under these constraints, the single-row pattern might deserve preference.

4.1 Introduction

Light interception is directly proportional to the total dry-matter production of crops (Monteith, 1977). This holds for the yield of fruit trees as well (Jackson, 1980; Hunter and Proctor, 1986; Barritt, 1989; Palmer, 1989a; Robinson and Lakso, 1989), although the partitioning of dry matter is also dependent on light distribution within the canopy: poor light distribution affects flowering, fruit set, fruit colour, size and chemical composition (Auchter et al., 1926; Lakso et al., 1989b). Field experiments have indicated that a high light interception together with a uniform light distribution favours yield and fruit quality (Wertheim, 1985; Wagenmakers and Callesen, 1989). This condition can be fulfilled by manipulation of tree density, spacing and shaping (Palmer and Jackson, 1973; Verheij and Verwer, 1973; Wertheim et al., 1986; Corelli and Sansavini, 1989; Wagenmakers, 1989a). In this respect multi-row systems ("beds") were expected to perform better than single rows at a given density. They can however produce fewer fruits per ha and show lower fruit quality (Wertheim et al., 1986; Engel, 1987). The causal factor is probably a reduced illumination of the inner rows. Light distribution can be improved by adjusting tree shape. Interactions between tree shape and spacing are complicated to deal with in field trials and besides, this kind of experiment with fruit trees takes many years. A simulation model for light transfer can help to provide a better understanding of the effect of the geometrical properties of trees and orchard systems. The principles of light transfer have been proposed by Monsi and Saeki (1953) for a one-dimensional canopy with layers of non-transmitting and non-reflecting leaves, where light penetration is a function of leaf projection normal to the solar beam, leaf density, and the pathlength through the canopy. Discontinuous canopies, such as orchards, need a more-dimensional approach. Two-dimensional models for parallel rows with closed canopy and uniform foliage distribution along the rows have been described for rectangular (Goudriaan, 1977), elliptical (Charles-Edwards and Thorpe, 1976) and triangular (Jackson and Palmer, 1979) cross-sections. Light interception is calculated by summing the various pathlengths across the rows. These models are adequate for infinite hedgerows. However, since many current fruit orchards consist of an array of individual trees rather than hedgerows, a three-dimensional approach is needed. Norman and Welles (1983) developed an extensive radiative transfer model for an array of individual ellipsoid sub-canopies that may be spaced in any manner desired, and included multiple scattering for visible and infra-red wavelengths, and emission for thermal wavelengths. The present study considers a simple model of the transfer of visible light for an array of individual plants of various shapes.

4.2 Structure of the model

The present model is based on that of van Kraalingen et al. (1989), who described light transmission for an array of hemispherically shaped oil palm trees on a triangular co-ordinate system. Modifications of their model for applicability to orchards involve the shape and spacing of the trees, and foliage distribution in individual trees.

Tree architecture

Fruit trees can be approximated by four types of crown shape (Figure 4.1). The cone and the parabola represent a slender spindle, which is commonly used in Dutch orchards with 2000 to 4000 trees per ha. A slender spindle consists of a central leader with scaffolds in the lower part of the tree and smaller laterals in the top. Its ultimate crown diameter usually ranges between 1 and 2 m and the height between 2 and 2.5 m. The cylindrical shape simulates a columnar tree, which is either a 'Wycik' (mutant of the apple cv. 'McIntosh' having no laterals), or a cordon tree, in which all laterals are pruned to only a few nodes. The cordon tree has a crown diameter of 30 to 45 cm. It is used in very intensive systems (up to 20,000 trees per ha). The cylindrical shape can also be found with larger tree diameters in less intensive systems. The intermediate form is a modified slender spindle with fewer and shorter lateral shoots in the upper part and lower branches kept in a more horizontal position. This type should guarantee better illumination in multi-row systems, where within-row shading can affect yield.

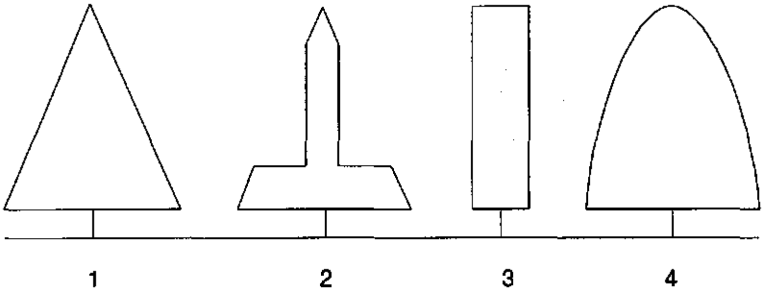


Figure 4.1

Model tree shapes: 1, cone; 2, intermediate; 3, cylinder; 4, parabola.

All trees are assumed to be similar as to shape and foliage distribution at a given spacing. The position of each tree is described by its field coordinates. Number and arrangement of trees may be chosen freely. Radius and height of the crown may vary, as well as the distance between the ground and the lower surface of the crown.

Light is absorbed by leaves, branches, and fruits, which are assumed to be uniformly distributed throughout the crown (Verheij and Verwer, 1973). In a first approximation, leaf and branch angle are assumed to have a spherical distribution without azimuthal preference. Fruits are considered simply as spheres, having the diameter of a fruit in an upright position (Palmer, 1977b). Underestimation of light absorption by ellipsoidal fruits such as pears is probably small and will be disregarded.

All plant structures are simply assumed to be black, thus neither reflecting nor transmitting light. This may underestimate light distribution within the canopy, since the reflectance and transmittance of apple leaves is about 8 and 3%, respectively, for most of the growing season (Palmer, 1977a).

Light transmission

Light intensity at a given point within the canopy is expressed as the fraction of incident light above it. The model distinguishes between direct and diffuse components of light. For a standard overcast sky, light transmission is calculated at ten-degree intervals over the hemisphere for 9 inclinations (5 to 85°) and 36 azimuths (0 to 350°). Integration values over these intervals have been given by Goudriaan (1977, p. 10).

Light transmission is calculated numerically. A line, representing the solar beam, is drawn from a given point within the canopy towards the sun. Its direction is determined by the inclination (b) and azimuth (a) of the sun (Goudriaan, 1977). The line is divided into discrete steps (s, in metres), its position being described by:

$$x = s \cos(b) \cos(a)$$

$$y = s \cos(b) \sin(a)$$

$$z = s \sin(b)$$

Over a short distance, the canopy is assumed to be homogeneous. If (x,y,z) are the co-ordinates of a point located within a crown, the light intensity at that location (T) can be calculated from the light intensity at the preceding point (T'), and the density of total plant area between the two points, in a plane normal to the solar beam:

$$T = T' \exp(-(k1\ LAD + k2\ BAD + k3\ FAD)\ s)$$

The extinction coefficients k1, k2 and k3 express respectively the average projection of leaves, branches, and fruit in the direction of the solar beam (de Wit, 1965; Goudriaan, 1988). The value of k is 0.5 for spherically inclined elements and 1 for spheres. Plant structures are limited to the tree crowns and are therefore expressed as densities, LAD, BAD, and FAD representing the area of leaves, branches, and fruits per unit crown volume, respectively. Where tree crowns overlap, the plant area density is multiplied by the number of trees involved. To express light transmission for a horizontal plane, this value is multiplied by the sine of solar inclination.

Evaluation of the consistency of the model

When the solar inclination is 90°, light transmission is independent of tree shape, spacing, and solar azimuth and is a function solely of plant area density and the height of the crown. Model consistency was tested by comparison of the model results with the analytical solution. This was done at various values for the step size (s). Putting s at about 1% of the canopy height gave results similar to the analytical solution.

4.3 Results

Verification of the model

The model was validated against the results of planting-system trials with pear (cv. 'Doyenné du Comice') and apple (cv. 'Golden Delicious') performed at Wilhelminadorp, The Netherlands. Tree shape was conic to parabolic.

In the trial with pear, trees were arranged at 2000 or 4000 trees per ha in single rows, or triangular three-row or five-row beds with oblique walking paths between the subrows within a system (Figure 4.2). Light interception was measured in June 1988 with cosine-corrected silicon cells, giving at least an 80% response to wavelengths between 465 and 645 nm. The cells were calibrated frequently against each other under similar exposure in the open, and occasionally against a standard instrument in the laboratory. Accuracy was within 5%. Records were taken under overcast sky conditions. One cell was located above the canopy, and one was shifted under the canopy at 25-cm intervals from the centre of one alleyway to the next along two to four tran-

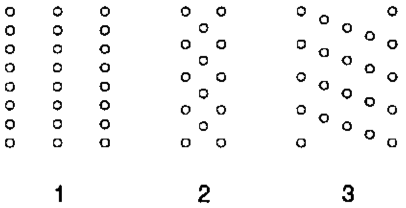


Figure 4.2

Experimental design of single row (1), triangular three-row bed (2) and five-row bed with oblique walking paths (3).

sects per plot (Wagenmakers and Callesen, 1989). Records were calculated relative to the readings above the canopy, and were averaged for four replicates per treatment. Leaf area was 7.7 and 6.1 m^2 and projected fruit area was 0.13 and 0.03 m^2 per tree for the lowest and highest planting density, averaged for the various planting systems, respectively. The projected branch area amounted to about 5% of the leaf area. Tree size was measured before new growth started. At that time, the trees were 2 to 2.4 m high, had a width of between 1.5 and 2 m, and were smaller at the higher planting density.

In the trial with apple, a single row at 2000 trees per ha and an intensive single-row system at 4000 trees per ha were compared, the latter with walking paths instead of alleyways ('full-field system'). The method of light measurement was slightly different from that given above. Cosine-corrected selenium cells were used with at least an 80% response in the 465 to 645 nm waveband (Palmer and Jackson, 1977). Sensitivity was checked frequently in the open. Up to 35 cells were set up under the canopy, spaced systematically over the area allocated to the trees. Three cells were kept above the canopy, one under a shade ring. Signals were recorded at 5-min intervals during at least one and a half cloudy day for each plot. Light interception was calculated from the total amount of diffuse light received over

Table 4.1

Simulated and observed light interception in planting systems for pear (1 – 6) and apple (7 – 8).

planting system	trees/ha	fraction of intercepted light		
		simulated		observed
		a	b	
1. Single row	2000	0.41	0.46	0.42
2. Three-row bed	2000	0.44	0.49	0.49
3. Five-row bed	2000	0.47	0.51	0.51
4. Single row	4000	0.47	0.53	0.53
5. Three-row bed	4000	0.49	0.56	0.53
6. Five-row bed	4000	0.51	0.57	0.59
7. Single row	2000	0.48	0.48	0.49
8. Full field	4000	0.67	0.70	0.74

a) tree size without current year's growth

b) tree size with 10 cm larger crown radius and height that period. Leaf area was 6.8 and 5.2 m^2, fruit area 0.45 and 0.34 m^2, height 2.4 and 2.2 m, and width 2 and 1.6 m per tree for the low and high density patterns, respectively (J.W. Palmer and S.J. Wertheim, unpublished data). Branch area was not measured and was ignored in the model calculations.

Table 4.1 lists the observed and calculated values for light interception. The model approximates the actual values quite well, although it tends to underestimate light interception when current year's growth is excluded from tree size. Better comparison was obtained when 10 cm was added to crown radius and height. Figure 4.3a shows the observed and the simulated light distribution in a five-row bed at two densities between row and alleyway centre. Figure 4.3b shows corresponding values for single row and full-field system of 'Golden Delicious'. The two patterns of light distribution are in close agreement, although there was overestimation of light transmission in the alleyway of the multi-row systems.

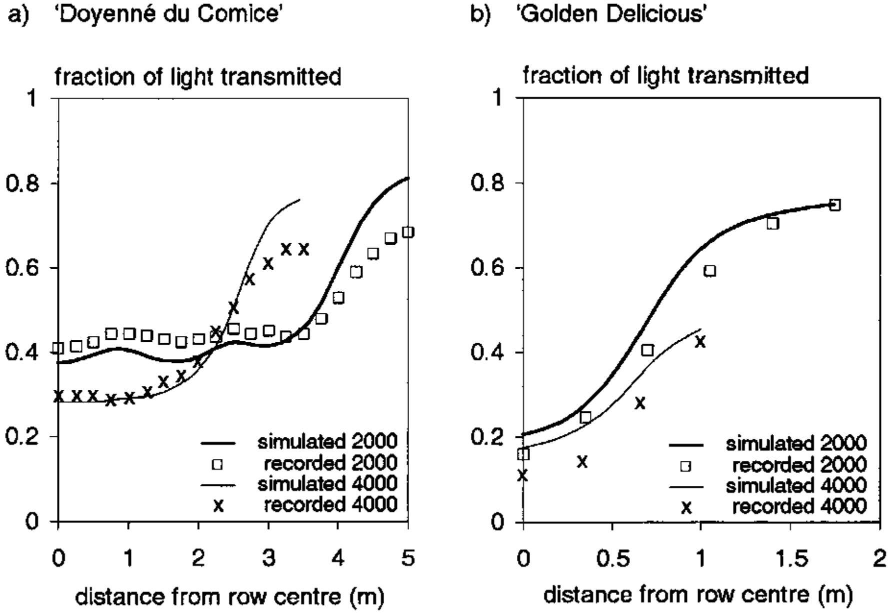


Figure 4.3

Simulated and observed light distribution for planting systems at 2000 and 4000 trees per ha for a five-row bed with 'Doyenné du Comice' (a) and for single-row systems with 'Golden Delicious' (b).

Effect of row configuration

The sensitivity of the model for the number of trees and rows included in a model system was investigated for a single-row system, in which trees have a height of 2 m and a diameter of 1.5 m. If the alleyway is 3 m wide (from trunk to trunk) and orchard LAI (m^2 leaf m^{-2} orchard surface) is 2 or more (full canopy), a good estimation of the diffuse light pattern is achieved with only one guard row at each side. Adding more guard rows did not influence light distribution.

Figure 4.4 shows the effect of tree position in the row on the diffuse light transmission at 3 locations (row centre, alley centre, and intermediate distance). Under the given constraints, the pattern of light distribution does not change from the second tree on. It is concluded that in spacing trials with spindle-type fruit trees, one guard row on both sides of the experimental plot and one guard tree at the head of each row will do to predict diffuse light distribution.

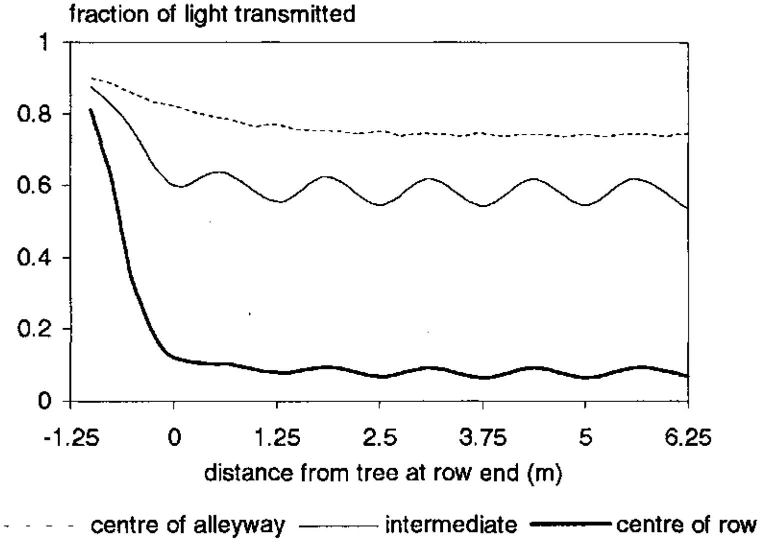


Figure 4.4

Simulated effect of tree position on diffuse light distribution along a single row.

Effect of tree shape and leaf characteristics

For a given tree height and crown radius, light interception increases in the order of intermediate tree shape, cone, parabola, and cylinder. At full canopy, intermediate tree shapes intercept 3% less light than cones do, 8% less than parabolas, and 16% less than cylinders. The effect of tree shape is most pronounced in the centre of the alleyway, where light levels are 38, 18, and 8% higher for intermediate tree shapes than for the cylinder, parabola, and cone, respectively. So, training of trees with a more slender upper part might considerably improve sidewards illumination.

Light interception increases with increasing tree height, but the latter factor interacts with leaf area per tree. To distinguish between these two factors, light interception is calculated for 3 tree heights (1.5, 2, and 2.5 m) at equal leaf density (thus at different leaf area) or at equal leaf area (and different leaf density). Tree shape and crown radius are taken as similar for all calculations. If leaf area increases with tree height, and leaf density does not change, light interception increases significantly with tree height in the range of 1.5 to 2.5 m. However, when leaf area is kept constant, the effect of tree height is reduced by half (Table 4.2). Tall trees with a lower leaf density have a better light penetration. So, trees are allowed to be higher if leaf density is reduced.

Table 4.2

Simulation of light interception (fraction) for three tree heights.

height (m)	constant leaf area	constant leaf density
1.5	0.51	0.47
2.0	0.55	0.55
2.5	0.58	0.62

Light interception is highly proportional to orchard LAI, particularly at lower LAI values. For a given single-row system, light interception increases linearly with LAI at values below 2. The effect of LAI is smaller at higher LAI values. Very small effects occur at LAI values greater than 3 to 4 (Figure 4.5).

Horizontal leaves have an average leaf projection equal to the sine of solar inclination and thus absorb more light at high solar heights than spherically inclined leaves. However, the model is not very sensitive to leaf inclination. At 52° northern latitude and in the middle of August, horizontal leaves in systems with a LAI of 2 intercept between 10:00 h and 12:00 h 2 to 3% more direct light than spherically inclined leaves. The latter intercept more direct light than horizontal leaves do at low solar heights (5% at 7:00). With an overcast sky, leaf inclination is not of any significance.

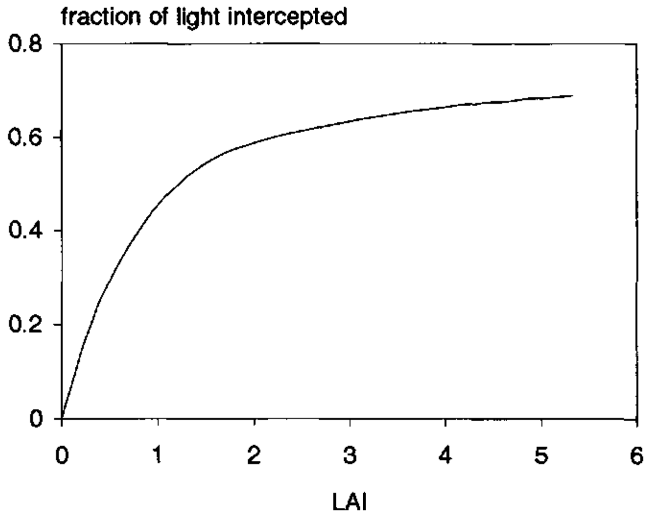


Figure 4.5

Simulated light interception as a function of LAI for a single-row system.

Effect of tree spacing

Both tree density and planting system can be used to manipulate light climate. Calculations were made for single rows and triangular three-row systems at various tree densities (Table 4.3). Tree dimension is the same for all

Table 4.3

Simulated light interception and recorded cumulative yield, averaged for two cultivars at two locations (Ge= Geldermalsen; Nu=Numansdorp) for single rows and three-row beds at a given tree size and different planting densities.

planting system	trees/ha	fraction of intercepted light	cumulative yield (tonnes/ha)	
			Ge	Nu
single row	2222	0.40	116	110
single row	2667	0.46	130	123
single row	3333	0.51	158	143
three-row bed	3155	0.52	162	131
three-row bed	3584	0.55	149	134
three-row bed	4329	0.56	160	136

treatments, resulting in different tree configurations. Trees have a free space of 25 cm at crown base at the lowest density for any given system, whereas crowns are touching at the intermediate density and overlap 25 cm at the highest density. This experiment was set up at two sites in The Netherlands with two apple cultivars ('Cox's Orange Pippin' and 'Gloster'). Leaf area was not recorded, but is assumed to be similar (8 m^2 per tree) for all treatments.

Table 4.3 shows data on simulated light interception and recorded yield of the first four cropping years. Both factors increase with tree density, three-row beds having a higher light interception at a given density than single rows. However, increase in light interception is very slight beyond 3584 trees per ha. Consequently, there was no further yield increase. Figure 4.6 shows light distribution patterns for the lowest and highest densities for each plant-

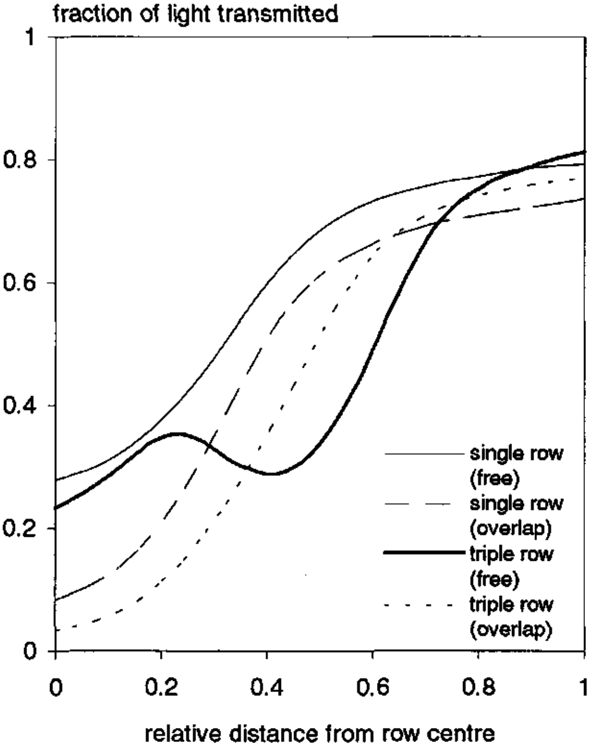


Figure 4.6

Simulated light distribution across a single row and a triangular three-row bed for similar trees at different planting densities.

ing system. The horizontal axis indicates distance as a fraction from row centre to alleyway centre. With increasing tree density, light levels decrease. It should be noted that the light penetration is greatly reduced in the centre of the three-row systems compared with outer trees and with single rows at a given tree configuration. This has not yet affected fruit colour in the trial in question, possibly due to the use of red strains, but fruit size declined with increasing density and was significantly lower in the three-row systems than in the single rows. The results point to the importance of light distribution for fruit quality.

4.4 Discussion

The model fits observed light distribution patterns under overcast conditions quite well. As such, it can be used as tool for optimizing the orchard system in terms of yield and fruit quality. It can also indicate the relative importance of the separate factors to be evaluated in field trials. This will reduce the need for long-standing field experiments.

The sensitivity of the model to crown size has been shown. Although the leaf density of one-year-old shoots is generally low, it might be more realistic to assume two shells of leaf density rather than a uniform distribution of leaves. This will improve comparison with actual values. If the purpose of the model is to analyse the behaviour of orchard systems, this item has less importance.

The choice of a wrong value for leaf area will lead to biased simulation results, in particular at LAI values lower than 3, as shown in Figure 4.5. The latter held for the measured plots. Leaf area was determined for a limited number of representative trees. However, leaf area can vary widely between trees, and interacts with crop load and pruning regime. Fruit area is small relative to leaf area and, therefore, contributes little to light interception. This finding confirms results of Verheij and Verwer (1973) and Palmer (1977b).

Although the assumed spherical leaf inclination generally represents a good first-order approximation (Goudriaan, 1988), a more planophile structure is probably more realistic for apple. In 'Golden Delicious' and 'Goldspur' trees, more than 80% of the leaves inclined less than 50° above horizontal (Rabbinge, 1976, pp. 108; Cervenka, 1978). Leaf angles of 11 to 35° above horizontal prevailed in 'Laxton's Superb' throughout the season (Jackson, 1970). However, since the model is not very sensitive to leaf inclination, the assumption of a spherical leaf-angle distribution seems justified. Denholm and Connor (1982) concluded the same for peach orchards.

Since diffuse conditions are predominant in The Netherlands, most emphasis was put on the distribution of this light component. The model predicts a better penetration of diffuse light than direct light does, which stresses the importance of the former for the photosynthetic response of a canopy (Denholm and Connor, 1982; Weiss and Norman, 1985). Our calculations support Lakso and Musselman (1976), who measured higher interior light levels on a partially cloudy day than on a bright, clear day.

A higher light interception can be obtained at higher tree densities. At any LAI, this can also be achieved with multi-row systems, but light penetration at the centre of the system is reduced, compared with single rows. Partial overlapping of tree crowns in multi-row systems does not significantly contribute to a higher level of light interception, but has a negative impact on the illumination of the row centre. Consequently, the actual performance of multi-row systems may be worse. Despite a lower level of light interception, a single row may perform as well as a multi-row system, due to a better lateral illumination.

The model predicts only a slight increase in light interception at LAI greater than 3. Such a high LAI will thus be inefficient in terms of productivity. Palmer (1989a) found for apple a maximum dry-matter production for LAI values between 3 and 4, and this was closely correlated with maximum light interception. Most temperate-zone orchards have, however, lower LAI values (Jackson, 1980), indicating that potential yield is not attained.

In conclusion, the present model can be used to deduce the effects of orchard geometry on light climate, and may be a helpful tool for the optimization of fruit yield and quality.

5 A model approach on optimal orchard design

Abstract

The role of planting system in the interception and distribution of light is discussed. Calculations on light transmission in three-dimensional tree canopies are validated in relation to measurements done in apple orchards with different planting systems. Measured and calculated values correspond, but deviations due to inaccurate estimation of leaf density or tree shape have been noticed. The model predicts that interception of more light can be achieved by increasing planting density, which can be combined with a more uniform light distribution and a higher percentage of well-illuminated crown volume unless leaf density is increased. Decreasing of the ratio of between-to-within row spacing will also lead to a higher light utilization. However, the combination of a higher tree density with increased ratio of between-to-within row spacing may not improve light utilization. Full-field systems can be considered as offering optimal spacings. Multi-row systems with walking paths between subrows intercept more light than do single rows with the same tree size. Bed systems on a triangular design are predicted to have more shaded canopy volume than do single rows. This is due to insufficient light transmission to the central trees.

5.1 Introduction

Since solar radiation provides the energy for photosynthesis, the production of total dry matter during any given season can be expressed as a function of the intercepted photosynthetically active radiation (Russell et al., 1989). Because fruit trees need a minimum illumination level for flower-bud formation and the development of various aspects of fruit quality, management aims at optimization rather than maximization of light interception (Jackson, 1978). A positive correlation between light interception and yield has been reported, but when light interception exceeds about 70%, flower-bud formation and the production of high-quality fruits may be reduced (Cain, 1971; Palmer et al., 1992). Furthermore, fruit yield is promoted by an even distribution of light through the canopy, which is explained by the non-linear response of photosynthesis to light.

Light interception is determined by the amount and spatial distribution of leaves. Small trees at high densities generally achieve greater light interception and a greater proportion of well-illuminated leaf area than do large trees at low densities. Consequently, the associated production increases with light interception and density (Forshey and McKee, 1970; Jackson, 1978; Robinson et al., 1993). Palmer et al. (1992) found a positive correlation between yield, light interception, and tree density up to 80% light interception and 8300 trees per ha. Data on higher densities are limited.

At a given density, light interception can be increased by applying a planting design with a low ratio of between-to-within row spacing (Jackson and Palmer, 1973; Wagenmakers and Callesen, 1989). In addition, these systems are characterized by a uniform light distribution. For example, full-field systems with a between-to-within row ratio of 1:1 or 2:1 have been found to produce about 30% more well-coloured fruit than row systems at 3:1 (Chapter 7). Because tractor access is also needed, the performance of low-rectangular full-field systems on a practical scale is approached by multi-row systems. Traditional multi-row systems, however, do not always intercept more light or yield more fruit than do single rows at a given density. On the contrary, yield can be even lower (Wertheim et al., 1986; Engel, 1987; Wagenmakers, 1989a), which might be due to insufficient light in the central parts of bed systems.

Further intensification of density may increase light interception and yield. A higher planting density, however, is often achieved from an increased rectangularity; since a certain alley width is needed for tractor access, the narrower planting distance has to be achieved within the row. This may increase leaf density, leading to less efficient light use. The interaction between planting density, rectangularity, tree size, and leaf density complicates studies on orchard systems and requires time- and area-consuming experiments. Light-interception models can be applied to analyse these interactions. Integration of empirical and physical information about the tree level might explain processes at the canopy level. Such models might provide leads for future experiments.

Study of the orchard system as a function of density, arrangement, and size of the trees requires a three-dimensional approach. Several models with varying complexity have been developed for three-dimensional light transmission in canopies. In a simple approach, leaves are assumed to be black, uniformly distributed within the crown or a given section of the crown, and without azimuthal preference. Canopy structure is represented by crown shape and size, and by tree density and arrangement (van Kraalingen et al., 1989). More complex models include specified functions of shoot structure, spatial distribution of shoots within the crown, scattering by leaves, azimuthal preference of leaves, and/or soil reflection (Oker-Blom et al., 1991; Myneny, 1991). The trees are approximated by fixed shapes. Norman and Welles (1983) applied ellipsoids, which have applications for many plant species. The assumption of homogeneous leaf distribution within the crown is a simplification, in view of leaf clustering around branches. Therefore, Mohren (1987) introduced a clustering coefficient and Myneny (1991) developed fractal geometry to simulate branching patterns of trees. The objective here is to evaluate the patterns of light transfer in various orchard systems as a function of tree density and arrangement by the use of a simple model. A model validation will be discussed for canopy light interception and light transmission inside apple tree crowns.

5.2 Calculating light transmission in planting systems

Light transmission

Light intensity (I) at a given point within or below the canopy is calculated on the basis of Beer's Law

$$I = I_0 \exp(-k\ LAD\ s)$$

where I_0 is incoming light, k is the light extinction coefficient, expressing the projection of leaves in the direction of the solar beam and depending on geometrical and optical characteristics of the canopy, LAD is leaf area per tree volume ($m^2\ m^{-3}$), and s is path length through the tree crowns (m). This equation holds for homogeneous canopies, but is also justified for discontinuous canopies by calculating light transmission numerically over short distances of s at a given LAD (van Kraalingen et al., 1989).

Leaves are simply assumed to be non-scattering, uniformly distributed within a crown, randomly orientated, and spherically inclined, with $k = 0.5$ in the direction of the solar beam (Goudriaan, 1988). Following Clayton-Greene et al. (1993), leaf-angle distribution is assumed to be the same for different orchard systems. The spherical inclination may lead to a slight overestimation of light transmission, for most leaves have an angle of about 10° below horizontal (Clayton-Greene et al., 1993). The model showed, however, a very small sensitivity to leaf-angle distribution (Wagenmakers, 1991c).

The calculations hold for a standard overcast sky (Goudriaan, 1977, pp. 41 – 46). Light interception is calculated from the mean percentage of transmitted light at the ground over a representative rectangular area between the centre of the row and the alleyway along cross-row lines. The minimum number of lines is two, one passing the tree and the other halfway between two trees centres. In the non-rectangular multi-row systems, more transects are considered, to allow for differences between outer and central trees. The cross-row interval is 10% of the distance between row centre and alley centre. For single rows a larger interval (20%) could be applied, because of smaller cross-row variation between two adjacent points. The pattern of horizontal light distribution is characterized by the average cross-row transect. The variation in cross-row light transmission, expressed as standard deviation (SD), is used as a measure for the evenness of light distribution, following Pukkala et al. (1991). Canopy light interception is derived from the mean values of transmitted light.

The trees are regarded as identical, parabolically shaped structures, circular in cross-section, and with a uniform leaf distribution. Light transmission within the tree crown is integrated numerically in the vertical direction between 0.1 and 0.9 of crown height (interval 0.2). Calculations in the horizontal plane are along circles at a distance of 0.4 and 0.9 of the crown radius, representing the inner and outer parts of the crown, respectively. The positions on the circle are considered at 8 equal intervals, starting normal to the row orientation.

To estimate the well-illuminated tree volume, the average value of light transmission at a given location is multiplied by its relative volume. The fractions of the respective height segments are 0.49, 0.29, 0.16, 0.05, and 0.01 for a parabolic tree, going from crown bottom to top, and those of the inner and outer circle are 0.64 and 0.36, respectively. The fraction of well-illuminated crown volume is calculated for a minimum of 10, 20, 30, 40, and 50% light transmission within the crown. Calculations are done for LAI values between 1.5 and 3.5, following common orchard values (Jackson, 1978; Wertheim et al., 1986; Robinson et al., 1993). LAI is defined as the one-sided, flat area of leaves per unit ground of row and alley. The fraction of well-illuminated tree volume multiplied by orchard LAI gives the illuminated LAI.

Tree dimension and planting system

The effect of crown height is not taken into account. The crowns are assumed to be 1.95 m high and the distance between ground and crown 0.25 m. These are usual dimensions for densities of 2000 and more trees per ha. Three types of planting system are considered: those having fixed values for the ratio of between-to-within-row distance(rectangularity), for alley width, or for tree diameter.

The theoretical effect of *rectangularity* is studied for two rectangularities (1.5:1 and 3:1). Tree size is supposed to be similar for the two rectangularities at a given planting density. This means that the trees are free-standing on 1.5:1, but overlap 10% within the row on the 3:1 design, respectively. Since the minimum free space between two rows is assumed to be 0.5 m, the associated maximum density is lower for the 1.5:1 design (15,000 trees per ha). To quantify the single effect of planting density and rectangularity, it is assumed that LAI, LAD, and canopy volume per unit ground area are similar (3 m^2 m^{-2}, 10 m^2 m^{-3}, and 0.3 m^3 m^{-2}, respectively) in all treatments.

The influence of a fixed *alley width* is evaluated for single rows with row distance of 3 m and a variable within-row distance of 1.25, 1.00, 0.75 or 0.50 m. Tree diameter follows within-row distance, such that the overlap within the row is 10%. Calculations are carried out for either constant LAI or constant LAD. The relationship between LAI and LAD is determined by canopy volume per ha.

Light interception of trees with similar *diameter* in different planting systems is evaluated on single rows, triangular three-row beds ('North-Holland sys-

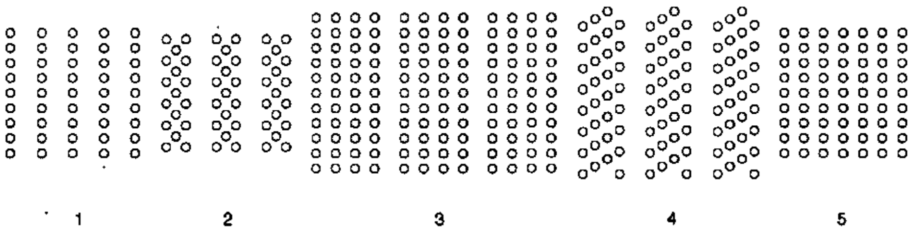


Figure 5.1

Design of planting systems: single row (1), triangular three-row bed (2), four-row bed with narrow paths parallel (3) or oblique (4) to alleyway, and full-field system (5).

tem'), four-row beds with walking paths directing either parallel or oblique to the alleyway, and full-field systems with walking paths instead of alleyways (Figure 5.1). For a given tree-to-tree distance within the row or sub-row (1.25 and 0.75 m), the alley width is 2.75 and 2.25 m, respectively. Tree diameter exceeds within-row distance by 10%. Calculations are done at a given LAI or LAD. For the latter, the LAD of the single-row with LAI of 1.5 is chosen as a standard.

5.3 Validation of the model

Light and leaf-area measurements

Light interception was measured under 2-year-old fruit-bearing trees of 'Cox's Orange Pippin' (hereafter abbreviated to 'Cox') and 'Alkmene' on rootstock M.9, arranged at 1.50 m between and 0.45 m within rows. Tree shape was cylindrical. Only diffuse light was recorded on overcast days with the use of silicon, cosine-corrected point sensors with a response of at least 80% between 465 and 645 nm (Technical and Physical Engineering Research Service, Wageningen). One sensor measured incident light above the canopy and one was moved at ground level between two row centres at a 0.25-m interval. Measurements were done in 2 replicates per cultivar on 5 dates between May and August of 1990. Leaf number was counted on 4 trees per cultivar close to the date of light measurement. The area of each 10th leaf was measured with the Delta-T Image Analysis System (Burwell, UK). Tree diameter was measured after the previous winter pruning and increased by 10% for new growth. The model calculations were done on the basis of cylindrical trees.

Within crowns, light transmission was measured in mature trees of apple 'Elstar' on rootstock M.9 instantaneously in the summers of 1989 and 1991. The trees were parabolically shaped. Light conditions were again diffuse. Data was collected in 1:1 arrangements with 2000, 2667, and 4000 trees per ha on 4 (2 in 1991) trees per density along a line centred on the trunk to the north, east, south, and west sides of the crown at levels between 25 and 200 cm above the soil, always at 25-cm intervals. Leaf number per tree was estimated and the area of each 20th leaf was measured with the Delta-T meter. Tree cross-section was ellipsoid, the within-row diameter being slightly greater. Since the model assumed a circular cross-section, separate calculations were done on the basis of the within-row and the cross-row diameter. Measured light transmission was compared with theoretical values by regression analysis. Student's T-test was used to identify differences in slope and intercept from 1 and 0 (P=0.05), respectively.

Comparison between estimated and measured results

Simulated and measured data on light interception are given in Table 5.1. The variation in measured light interception between replicates was 5% (data not given). 'Cox' intercepted slightly more light than 'Alkmene', despite leaf area was lower. This may be explained by its wider branch spread. Since the number of trees affecting canopy light interception exceeded the number of actually sampled trees, calculations and observations may diverge. The deviation between model and measurements was less than 10%. For 'Cox' in July and 'Alkmene' in August, however, differences were larger, that may be due to inadequate measurements. The measured light interception on those dates was not in agreement with leaf area, or with data on global radiation, continuously collected during the growing season in the same plots with solarimeters (unpublished data).

Simulated values of light transmission (y) were linearly related to measured data within the 'Elstar' crowns (x), following

$$y = 1.06\ x - 1.78 \qquad (r^2 = 0.78,\ n=233)$$

with SE values for slope and intercept of 0.04 and 0.92, respectively. Slope and intercept did not significantly differ from 1 and 0 (P=0.05), respectively

Table 5.1

Measured (a) and simulated (b) light interception (%) and measured leaf area (m^2 per tree) for two cultivars. Dates refer to light measurement.

	'Cox'			'Alkmene'		
date	light interception		leaf area	light interception		leaf area
	(a)	(b)		(a)	(b)	
7 May	33	33	0.24	30	32	0.29
29 May	43	43	0.38	39	41	0.43
11 June	51	51	0.51	56	58	0.87
4 July	60	50	0.49	55	60	0.97
22 August	53	57	0.68	50	63	1.07

(Figure 5.2). Separate analyses for the various transects per year, density, and orientation confirmed that predicted values did not differ significantly from measured values, except for some transects in E-W direction, i.e. those of 1991 at 2000 (slope = 1.2) and 2667 trees per ha (intercept = –6.3), and those of 1989 at 4000 trees per ha (slope = 1.25, intercept = –6.9). In all transects, LAD varied between 6 and 12 m^2 m^{-3}, and increased with planting density. Leaf distribution within the crown was, however, not uniform. Generally, the shoots facing outward had a lower LAD than inner tree parts. Obviously this was more pronounced in the E-W direction than within the row, where tree crowns overlapped partly. As a consequence, certain predictions, particularly for the E-W direction, overestimated light transmission.

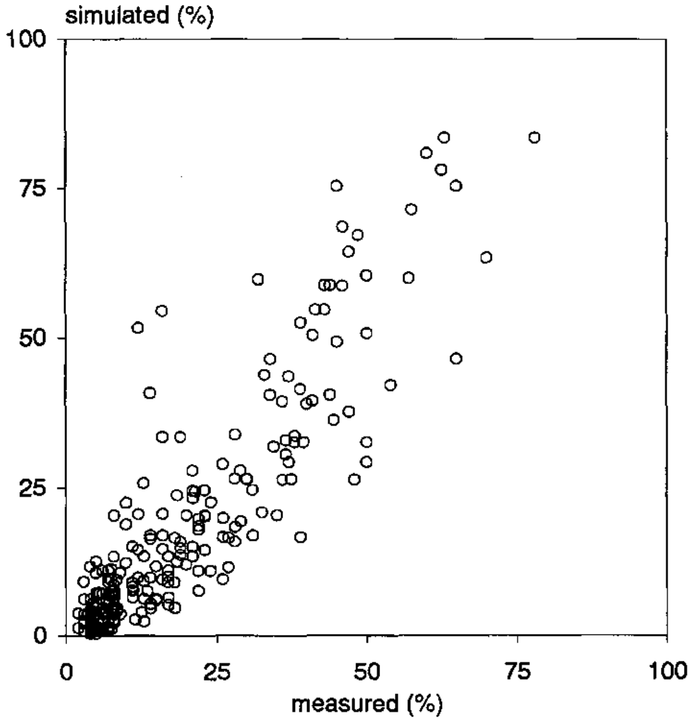


Figure 5.2

Comparison of simulated and measured light transmission within 'Elstar' trees at densities 2000, 2667, and 4000 trees per ha for two years and in directions normal and parallel to the row.

5.4 Simulation results

Rectangularity

The 1.5:1 designs intercepted more light than the 3:1 designs did. For both rectangularities, light interception increased with planting density. At about 12,000 trees per ha, a plateau level was achieved for the lower rectangularity. A similar maximum light interception was achieved at 20,000 trees per ha for the 3:1 design (Figure 5.3). The 3:1 designs showed a greater variation in horizontal light transmission. SD was 10 and 15 for 1.5:1 and 3:1 designs, respectively, when averaged for densities between 3000 and 15,000 trees/ha. As planting density increased, SD decreased markedly from 21 at 3000 to 8 at 15,000 trees/ha, averaged for both rectangularities. The well-illuminated crown volume increased only slightly with density and was slightly better in 1.5:1 than in 3:1 designs (data not shown).

Alley width

When within-row distance decreased but alley width remained the same, light interception even decreased with increasing planting density for a given

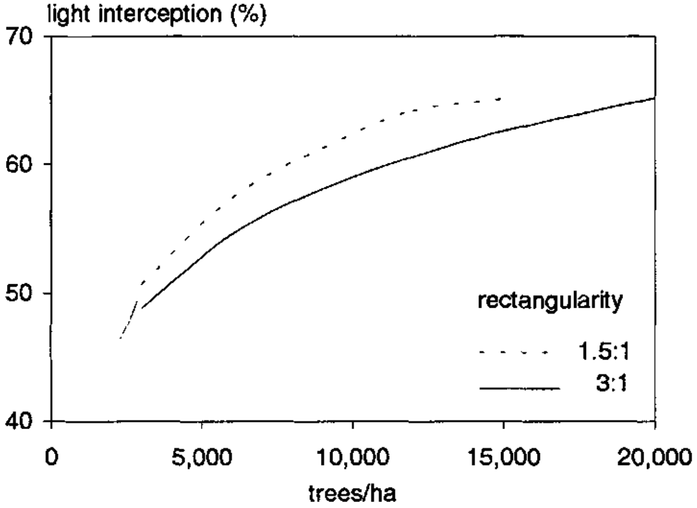


Figure 5.3

Canopy light interception at two rectangularities, assuming similar LAI and LAD at all densities.

LAI (Table 5.2). The more uniform light distribution at the narrower spacings, as expressed by a lower SD, was due to light transmission on the row centre, that increased from 10% at 1.25 m to 29% at 0.50 m within-row distance. Transmitted light in the centre of the alleyway was quite similar among densities (data not shown). In contrast to the more uniform light distribution at the ground, the crown illumination was not better at higher densities. On the contrary, the increased LAD led to a marked decrease of well-illuminated leaves.

Table 5.2

Canopy light interception, standard deviation of horizontal light transmission at ground level (SD), well-illuminated tree volume, and well-illuminated LAI at four within-row spacings and a between-row spacing of 3 m

trees per ha	2667	3333	4444	6667
within-row distance (m)	1.25	1.00	0.75	0.50
constant LAI				
LAI	3.0	3.0	3.0	3.0
LAD	7.8	9.7	13.2	18.7
light interception (%)	53	49	45	41
SD	26	24	21	16
well-illuminated crown (%)	24	21	13	11
well-illuminated LAI	0.7	0.6	0.4	0.3
constant LAD				
LAI	3.6	2.9	2.1	1.5
LAD	9.3	9.3	9.3	9.3
light interception (%)	57	49	43	36
SD	28	24	19	14
well-illuminated crown (%)	19	23	27	35
well-illuminated LAI	0.7	0.7	0.6	0.5

Assuming a fixed LAD, light interception decreased even more with increasing planting density than at a constant LAI. More light penetrated into the tree at a narrower within-row distance, which was obviously attributable to the wider free alleyway. The well-illuminated LAI, however, still decreased with increasing planting density, although less dramatically than for the above case.

Tree diameter

For a given tree-to-tree distance, light interception increased going from low-density single rows to higher-density multi-row systems, even when LAI would be the same (Table 5.3). The increase in light interception was obviously more pronounced when LAI increased with density. The increase in light interception was associated with a more uniform light distribution (expressed by lower SD) and a higher area of well-illuminated leaves.

The illuminated canopy was always higher on four-row and full-field systems than on single rows, even when LAD was slightly higher. Multi-row systems with walking paths parallel to the alley were slightly better illuminated than systems with oblique paths possibly as the consequence of a slightly wider path. Three-row beds, however, were illuminated less well than four-row beds, which is entirely ascribed to arrangement, since it was found even when planting density would be the same (i.e., 3760 trees per ha). The less efficient light use of three-row beds was mainly due to extremely low light transmission to the central row, as illustrated in Figure 5.4.

For a given planting system, a higher LAI will not necessarily lead to better light use by the canopy. On the contrary, light interception increased only

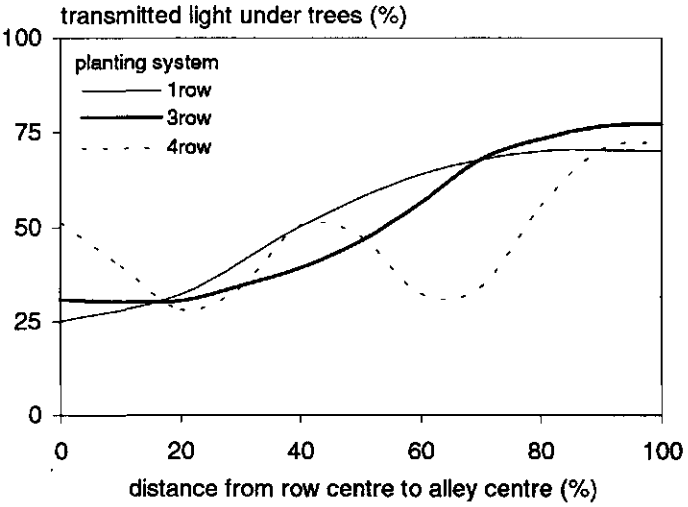


Figure 5.4

Illustration of cross-row light transmission under the trees for three planting systems with similar tree size and LAI.

little, whereas crown illumination was even considerably reduced, despite a more uniform distribution on the ground in some of the higher-density planting systems. This may be attributed to a higher LAD.

Table 5.3

Canopy light interception, standard deviation of horizontal light transmission at ground level (SD), and well-illuminated LAI for single rows, three-row beds on triangular design, four-row beds with walking paths oblique or parallel to the alleyway, and full-field systems, for a range of low and high planting densities, assuming either LAI or LAD constant.

	single row	4-row bed "oblique"	3-row bed "triangular"	4-row bed "parallel"	full field
Low tree densities					
trees per ha	2910	3760	3760	4000	4570
fixed LAI					
LAI	1.5	1.5	1.5	1.5	1.5
LAD	3.6	2.8	2.8	2.6	2.3
light interception (%)	48	52	52	53	57
SD	20	18	21	15	9
well-illuminated LAI	1.0	1.2	1.1	1.4	1.5
fixed LAD					
LAI	1.5	1.9	1.9	2.1	2.4
LAD	3.6	3.6	3.6	3.6	3.6
light interception (%)	48	57	56	59	67
SD	20	20	23	17	12
well-illuminated LAI	1.0	1.2	1.1	1.3	1.4
High tree densities					
trees per ha	5925	7790	8550	8890	9375
fixed LAI					
LAI	1.5	1.5	1.5	1.5	1.5
LAD	5.0	3.8	3.4	3.3	2.8
light interception (%)	47	50	51	53	58
SD	14	18	19	14	7
well-illuminated LAI	0.9	1.2	1.2	1.4	1.5
fixed LAD					
LAI	1.5	2.0	2.2	2.3	2.7
LAD	5.0	5.0	5.0	5.0	5.0
light interception (%)	47	54	56	60	70
SD	14	20	22	16	9
well-illuminated LAI	0.9	1.0	1.1	1.1	1.3

5.5 Discussion

Significance of the model

If the canopy is approached as an arrangement of trees with identical size and leaf area, any prediction of light distribution will be a simplification. Still, comparisons between calculated and measured results suggest that the model realistically estimates light transmission for a wide range of planting densities.

A crucial point is the estimation of LAD, defined by tree size and leaf area. The tree-to-tree variation of these parameters may be large, which is mainly due to crop load (Maggs, 1963). Unfortunately, the number of observations is often limited, most likely because the direct measurement of leaves is labour intensive. Having indirect, non-destructive techniques for measuring LAI and leaf distribution would be very useful. Empirical correlations with vegetative characteristics of the trees probably only have limited application. Palmer (1987) found a good correlation between leaf area and trunk circumference for young trees, but not for older ones. The measurement of light transmission may provide more accurate estimates of leaf area. In this respect, several portable sensors may be useful for measurements in discontinuous canopies. Lang and Yueqin (1986) measured the transmission of direct light by including local gap frequency, and confirmed their analysis in crops of sorghum and wheat. Grantz et al. (1994), working with cotton, made use of a commercially available instrument (LAI-2000 plant canopy analyzer, LiCor Inc., Lincoln, USA), which should work under all-sky conditions, although a cloudy sky would be best.

A more complicated model, simulating a canopy with trees of divergent LAD, may account for the spatial variation in leaf distribution between trees. In addition, including a function for leaf distribution per tree may increase the validity of the model as a tool. For apple trees, probably two concentric circles will be sufficient, representing outer and inner sections. Palmer et al. (1992) reported a lower LAD for outer than for inner sections and Clayton-Greene et al. (1993) distinguished a different leaf orientation for inner and outer parts. It is a practical problem, however, to define exactly the inner and outer section of a tree.

Because of the large variation in actual LAD, the value of the present model is primarily for the comparison of light distribution in planting systems rather than for predicting absolute values. Furthermore, the calculations can be used to support advice to growers on tree and orchard management. The model may extend to other crops with clustered leaves. From the viewpoint of light, the dimensions of a crop are not relevant for the model and may range from flower bulbs to forest trees.

Light distribution in planting systems

The values on light transmission on the ground inform indirectly about patterns of light absorption by the crowns. In general, an even light distribution will favour production. Pukkala et al. (1991) used SD-values with reference to the growth of understorey plants in forests. Our findings indicate that a uniform distribution (low SD) is not necessarily correlated with greater light interception or better illumination within the canopy (Table 5.2). This was dependent on increased LAD or decreased LAI with increasing planting density. A higher level of lateral illumination from the alleyway (high SD) can even reduce the negative effect of increased LAD within the row, particularly in the lower parts (Oker-Blom and Kellomäki, 1983). The use of SD as a measure of fruit productivity should therefore only be applied when data on light interception and within-tree light distribution are included.

Orchards with densities increasing from 2000 to 4000 trees per ha have been developed to achieve better economic results. Further intensification of density may still improve the economic yield, although Goedegebure (1993) reported that the results are strongly dependent on production level and fruit quality. On the basis of light, our calculations suggest that planting densities higher than 4000 may indeed offer better possibilities related to greater light interception and a better-illuminated crowns as a result of the distribution of leaves over a larger number of trees. Low rectangularities are preferred, for it has been predicted that 3:1 designs require considerably more than 1.5:1 designs for the same light interception (Figure 5.3). Grace (1988) calculated a difference of 20% light interception between rectangularities 1:1 and 7:1 at a given density. Differences may be even greater when trees at low rectangularities, having more space per tree, would grow larger than in higher rectangularities (Wagenmakers and Callesen, 1989). In that case, however, care should be taken to prevent critically high levels of shading. It should be noted that in many orchards, higher planting densities are not coupled with an adequate reduction in alley width (Robinson et al., 1993). As a consequence, rectangularity increases and light interception is inadequate. For example, apple orchards, that combined a very high density (16,700 trees per ha) with a high rectangularity (7:1) have been found to intercept only 30% of available light (pers. data). High-rectangular systems would need more leaf area to reach adequate light interception, but even then, the increase in well-illuminated canopy can be limited, because of increased leaf clumping.

Our calculations support observations on the productivity of different planting systems, which generally increases from single row to multi-row bed and full-field system. This sequence is explained by both tree density and orchard configuration. Full-field systems are very efficient, since even with a lower LAI they intercept more light than row systems do (Palmer and Jackson, 1973). It has been calculated that multi-row systems with walking paths can only be considered as an acceptable compromise between single rows and full-field systems if leaf density were not increased. A higher LAD, however, may be characteristic for higher planting densities (Palmer et al., 1992). Control of leaf area is therefore necessary when a higher planting density is pursued.

Three-row bed systems on a triangular design have been reported to have similar or even lower yields and quality than other systems (see under Introduction). The calculations suggest that this may be due to excessive shading of the central rows, which is more pronounced than in systems with walking paths. It is recommended to develop a modified tree shape with a very slender top, that permits more light into the centre of a multi-row system but does not lead to insufficient light interception.

On balance, the optimal planting design for orchards with respect to light can be found in a high density as well as a low rectangularity. By planting multi-row beds with paths that provide sufficient light into the trees, the number of trees per ha needed for a given light interception can be considerably lower than on single rows, because of a more uniform distribution of light. The benefit of intensification is doubtful, when accompanied by an increased LAD. In that case, the shaded tree volume will increase, which affects fruit growth and quality negatively. Failures can also be expected when the canopy volume is insufficient for adequate light interception and yield, a situation that may occur when rectangularity is increased together with planting density. The use of models describing light distribution in the optimization of planting density, planting system, and leaf density was demonstrated. These models may be used in strategic decision making.

6 Planting system and pruning regime

Summary

Two tree shapes, the slender spindle and the North-Holland spindle, were studied in four planting systems (single row, three-row bed, six-row bed, and full field) at high plant densities. Additional summer pruning was applied to half of the trees in each system. The trial was performed with apple cultivar 'Red Boskoop' on a soil type characterized by moderate growth vigour. The trunks of the North-Holland spindle grew less than those of the slender spindle. Tree density and pruning intensity were negatively correlated with trunk-basal area increment. The North-Holland spindle, which had nearly 500 more trees per ha, yielded as much as the slender spindle. For a given density the North-Holland spindle yielded less than the slender spindle. Yield efficiency, expressed as cumulative yield per unit of final trunk-basal area, was also lower for the North-Holland spindle. However, per unit of crown volume, this spindle type produced considerably better. The additional summer pruning did not affect yield or yield efficiency. The influence of planting system was small and of minor importance compared with planting density. Single-row systems tended to yield more, and three-row systems less, than the other systems, as shown by linear regression analysis. The slender spindle had more flower clusters and cropped more irregularly than the North-Holland spindle. Additional summer pruning slightly promoted flowering of the North-Holland spindle and decreased that of the slender spindle. It decreased biennial bearing of the slender spindle whereas the North-Holland spindle cropped more biennially with summer pruning.

6.1 Introduction

High-density planting has been an important development of recent decades in Europe, and has led to increased productivity and earlier yields. In The Netherlands at present, apple orchards are fully productive from the fifth growing year and start yielding even in the second. Much attention has been given to controlling the balance between growth and fruit production in high-density plantings. Although dwarfing rootstocks are of prime importance for controlling growth, cultural techniques such as pruning and orchard design also have an influence on tree development.

The importance of radiation in relation to flowering and yield is well known (Cain, 1972; Jackson, 1978). Tree volume is important for light distribution, small trees having a better light climate than large, voluminous trees in which radiation can be very low in the inner parts. However, smaller trees are planted at higher densities to obtain the necessary production capacity, but this increases the inner-tree competition for light. The slender spindle (Wertheim, 1970) is one of the common tree shapes now used in high-density plantings. The tree is conical, with an ultimate basal diameter of 1.50 to 1.75 m after winter pruning. Another tree shape frequently used is the North-Holland spindle (Flierman, 1977). This type is more slender than the

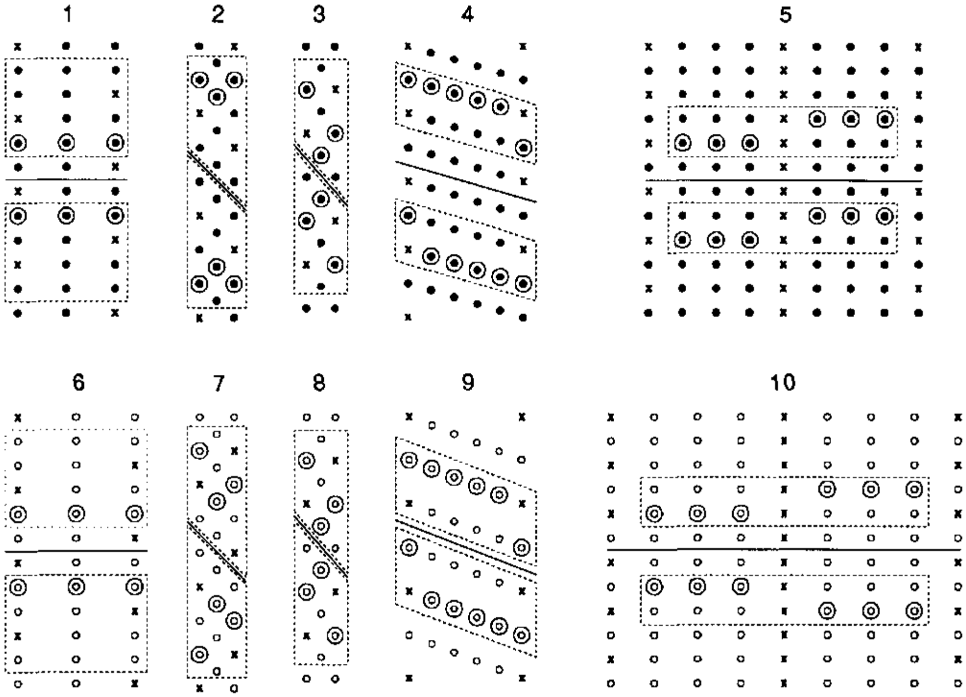


Figure 6.1

Arrangement for North-Holland spindle (1–5) and slender spindle (6–10): single row, three-row bed (narrow + wide), six-row bed, full field. ⊙, ◎ = observation tree for yield, flowering, and trunk girth; x = pollinator; enclosed: trees for yield observation.

slender spindle, having a basal diameter of 1.0 to 1.5 m. Tree height of both types is 2.0 to 2.25 m. The dormant pruning of the North-Holland spindle consists particularly of shortening branches, whereas the slender spindle branches are not only shortened or headed, but are thinned and cut away as well. The North-Holland spindle receives more small cuts than the slender spindle, resulting in more extension shoot growth per tree.

With respect to arrangement, considerable land area is sacrificed for alleyways with intensive single-row systems. At the same tree volume, more trees can be arranged per ha in multi-row systems. Although the efficiency of land use is higher (Jackson, 1980), the inner rows of the system may suffer from shading by adjacent trees, which reduces production capacity (Wertheim et al., 1986). Full-field systems comprise single-rows with walking paths instead of tractor alleys, having alleyways at regular intervals either longitudinally or transversely. The utilization of light and space is very efficient, but since current mechanization has not been adapted, these systems have not yet been used in commercial orchards. Both systems require quantification of yield and growth, and the optimal tree shape has to be evaluated for each of these planting systems.

Growth is regulated by dormant pruning, but summer pruning may be useful as well. Shoot growth can be reduced by summer pruning. For bearing trees, however, secondary growth of the trunk and branches is reduced more than shoot growth (Marini and Barden, 1982a; Rom and Ferree, 1984b; Taylor and Ferree, 1984a). Partial removal of the current year's shoots does not affect yield in general, but reduction in fruit size has been observed after very severe summer pruning (Marini and Barden, 1982c).

Although flower-bud initiation may even start at bloom, the condition of the buds is unstable and reversion to the vegetative stage occurs frequently (Landsberg and Thorpe, 1975). The final number of flower buds is influenced by weather, crop load, and carbohydrate supply. Summer pruning may influence both the light environment and the carbohydrate level. Several authors have found reduced flower density after pruning (Lord et al., 1979; Hansen and Grauslund, 1980; Marini and Barden, 1982a). This effect was more pronounced at higher pruning intensity.

The present report is concerned with the importance of tree shape, arrangement, and additional summer pruning on trunk basal-area increment, yield, and flowering in high-density plantings, evaluated in 'Red Boskoop' apple trees during eight growing seasons.

6.2 Material and methods

A trial on cultivar 'Red Boskoop' (rootstock M.9) was planted in 1978 at Wilhelminadorp, The Netherlands, for the evaluation of two conical tree shapes, the slender spindle and the North-Holland spindle. The basal diameter of the slender spindle after winter pruning was 1.75 m in the adult phase and that of the North-Holland spindle 1.25 m. The tree heights were 2.25 and 2.00 m, respectively, with a crown height of 1.75 for both. Five planting systems were under study (single row, three-row beds at two plant densities, a six-row bed, and a full-field system, see Figure 6.1). The inner trees of the three-row beds were surrounded by four trees. The six-row bed was supplied with a walking path with a free space of 0.50 m after winter pruning, the middle tree in the bed being opposite the middle of the entrance to the path. The full-field system consisted of a rectangularly planted single-row system with a walking path of 0.50 m instead of a tractor alley. Sets of nine rows were separated by a tractor alley giving 1.25 m of free space.

Since planting distances were determined by tree diameter, density was not the same for all treatments (Table 6.1). Averaged over all planting systems, the North-Holland spindle had 469 trees per ha more than the slender spindle. Crowns of the North-Holland spindle met after winter pruning, whereas

Table 6.1

Planting systems and densities in the present study.

tree shape	planting system	planting distance (m)	trees/ha
slender spindle	single row	3.00x1.25	2667
	three-row bed (wide)	3.00+(2x0.75)x2.25	2959
	six-row bed	3.00+(5x1.17)x2.25	3012
	full field	2.25x1.25	3203*
	three-row bed (narrow)	2.75+(2x0.89)x1.75	3788
North-Holland spindle	three-row bed (wide)	3.00+(2x0.75)x2.25	2959
	single row	2.50x1.25	3195
	three-row bed (narrow)	2.75+(2x0.89)x1.75	3788
	six-row bed	2.75+(5x1.20)x1.75	3922
	full field	1.75x1.25	4109*
means for tree shape			
slender spindle			3126
North-Holland spindle			3595

*per 0,9 ha

those of the slender spindle had an overlap of 0.50 m at the crown base. The overlap was placed in the row direction for single row and full-field system and in the walking-path direction for a six-row bed. The inner trees of the three row beds shared their portion with four surrounding trees. The three-row bed was planted at two densities, according to the dimensions of the two spindle types. Half of the trees per system were pruned only during dormancy and the other half received an additional light summer pruning, three to four weeks before harvest.

The free tractor-alley width was 1.25 m in summer for all systems. Rows and beds were oriented N-S, the walking paths in the six-row beds lying NNW to SSE. Pollination was provided by 'Discovery' on rootstock M.9 in 20 to 23% in all treatments (Figure 6.1).

For the four replicates arranged in an block design, two pruning regimes were assigned randomly, i.e. winter pruning with and without summer pruning. These regimes were used in five planting systems subdivided into ten treatments, each applied to the tree shape of a slender and of a North-Holland spindle. For each replicate, flower clusters were counted and trunk girths measured on three trees per treatment in the six-row bed and the full-field system. For the three-row beds these trees represented one inner tree on two outer trees. For the six-row beds four inner trees and two outer trees were used. Production was determined for six trees per treatment in the single row and the three-row beds, and for twelve trees per treatment in the six-row and the full-field system. Yield data expressed as kg per tree were collected annually up to 1985, the eighth growing season. Flower clusters were counted annually in the mouse-ear stage up to 1986. Trunk girth was measured annually in the dormant season, 0.25 m above the union, up to the winter of 1984 / 1985. Tree volume (V) was calculated according to the formula for a cone, $V = 1/3\ \pi\ r^2 h$ in which r is tree radius and h is crown height, based on crown dimensions after winter pruning. Data were evaluated statistically by analysis of variance for a split-plot design. Regression analysis was done within the analysis of variance. Bienniality intensity was calculated for yield and flowering according to Pearce and Doberšek-Urbanc (1967). An index was calculated for the 1981–1985 period, depending on the sum of the differences in yield (y) of two succeeding years, divided by the sum of the yield of those years, according to

$$I = 0.25\left[\frac{y(1981-'82)}{y(1981+'82)}+\frac{y(1982-'83)}{y(1982+'83)}+\frac{y(1983-'84)}{y(1983+'84)}+\frac{y(1984-'85)}{y(1984+'85)}\right]$$

An index value of 0 indicates no alternate bearing, whereas 1 indicates complete on- and off-years. In the present study, the biennial effects of the treatments were studied rather than the bienniality of 'Red Boskoop' as a cultivar. Therefore, means of trees per treatment were applied instead of individual trees. The same trees were used for the bienniality analysis of flowering and yield.

6.3 Results

Growth

Table 6.2 represents the increment in trunk-basal area for each tree shape and planting system over the eight years from planting. The additional summer pruning reduced growth in trees of all treatments. Trunks in single rows grew significantly better than those in the multi-rows, averaged for tree shape and pruning regime. Averaged over all planting systems, the slender spindle trunks became significantly thicker than those of the North-Holland spindle. At the same density, growth of the North-Holland spindle tended to be reduced more than that of the slender spindle. The decrease in trunk-basal area (a) of both tree shapes was linearly related to planting density (n) as described by the equation

$$a = -0.00142\,n + 13.4 \qquad (P \leq 0.001) \qquad (6.1)$$

Production

Table 6.2 shows the cumulative yield per ha for the first eight years after planting. Because the yield was the same after the summer and dormant pruning, the data were averaged, but because of the significant interaction between the tree shapes, the relevant data were analysed separately. The full-field-system of the North-Holland spindle yielded more than the other systems. This was also the case for the slender spindle, but here, the high-density three-row bed matched the full-field system. On average for all planting systems the slender spindle produced 9 tonnes per ha more than the North-Holland spindle. Production per ha (y) was linearly related to planting density, according to the equations

slender spindle: $y = 0.0401\,n + 196$ (6.2)

North-Holland spindle: $y = 0.0303\,n + 201$ (6.3)

These equations were not significantly different in slope or intercept (slender spindle: SE (slope) = 0.0174, SE (intercept) = 54.7; North-Holland spindle: SE (slope) = 0.0159, SE (intercept) = 57.5).

Three-row systems of both tree shapes, having the same tree densities, were also analysed separately to mitigate the confusion of density and spatial arrangement. At a given density in these systems, the slender spindle

Table 6.2

Increase in trunk-basal area over the first eight growing seasons, yield in the eighth growing season, cumulative yield expressed per unit of orchard area, tree volume, and trunk-basal area, and the numbers of flower buds, averaged for the fifth/sixth and seventh/eighth growing seasons.

	trunk increase	1985 yield	1979–1985 cumulative yield			flower buds /ha
	cm^2	tonnes /ha	tonnes /ha	kg/m^3	kg/cm^2	x10^3
slender spindle						
single row	10.7	69	306	96	5.4	484
three-row bed (wide)	8.9	63	297	84	5.5	542
six-row bed	8.9	59	309	86	5.6	509
full field	8.7	69	329	86	5.7	514
three-row bed (narrow)	7.9	82	352	77	5.5	591
LSD$_{0.05}$	1.2	13	32	8	0.6	76
North-Holland spindle						
three-row bed (wide)	8.1	58	279	155	5.6	357
single row	9.4	66	317	162	5.3	418
three-row bed (narrow)	7.2	59	302	131	5.2	442
six-row bed	7.7	61	318	133	4.9	469
full field	7.4	68	332	133	5.0	474
LSD$_{0.05}$	1.2	8	21	10	0.6	51
means for tree shape						
slender spindle	9.0	68	319	86	5.5	528
North-Holland spindle	8.0	63	310	143	5.2	432
LSD$_{0.05}$	0.8	–*	–*	4	0.4	–*
means for pruning regime						
winter	9.1	65	315	115	5.1	483
winter + summer	7.9	65	313	114	5.6	477
LSD$_{0.05}$	2.2	14	16	5	0.7	–*

* no value due to interaction

yielded 325 tonnes per ha, and the North-Holland spindle 290. This difference was significant(at P=0.01), and was even more pronounced in the narrow three-row bed than in the wide three-row bed. The former yielded significantly more than the latter (at P=0.01) for both tree shapes.

The tree volume of the slender spindle was 1.21 m^3, whereas that of the North-Holland spindle was 0.61 m^3, based on the dimensions given before. The cumulative yield per tree volume was significantly higher with the North-Holland spindle, as was the yield of single rows compared with the multi-row systems (Table 6.2). In these calculations, the tree overlap of the slender spindle was not taken into account. The theoretical volume of overlap between two adjacent trees was 0.16 m^3. This would enhance the yield per tree volume of the slender spindle by 6 to 9 %, depending on planting system. Still, differences between both tree shapes would remain high.

Yield efficiency was expressed as cumulative yield per unit of final trunk-basal area measured in the spring of 1985. Although summer pruning promoted efficiency, the differences were not significant (at P=0.10). Marked residual variation masked the eventual effects of the planting system. The slender spindle was slightly more efficient than the North-Holland spindle, and planting density had no effect on yield efficiency.

Figure 6.2 shows the build-up in yield for the first eight years of the slender and North-Holland spindle, averaged for all planting systems. The rapid increase in production in the

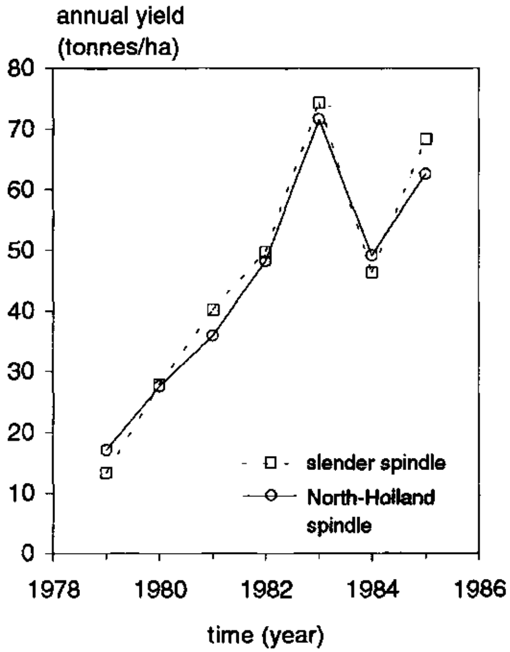


Figure 6.2

Annual yield per ha, averaged for planting system and pruning regime.

first five years and the small differences between the two spindle types at maturity are clearly shown.

Summer pruning did not affect production in 1985 (Table 6.2). Because of the interaction between tree shape and treatments, data of this year were analysed separately. Yield of the slender spindle still increased linearly with density, although weakly. However, this was not significant for the North-Holland spindle. On average for all treatments, the slender spindle yielded slightly more than the North-Holland spindle. The eventual effects of the planting system were mainly outstripped by biennial effects.

Table 6.3

Bienniallity index for number of flower clusters and fruit weight per tree (1981 – 1985)

treatment	bienniality index: flower clusters (no.)	bienniality index: fruit weight (kg)
slender spindle		
single row	0.53	0.31
three-row bed (wide)	0.62	0.28
six-row bed	0.39	0.17
full field	0.32	0.20
three-row bed (narrow)	0.58	0.28
$LSD_{0.05}$	0.08	0.06
North-Holland spindle		
three-row bed (wide)	0.28	0.18
single row	0.32	0.18
three-row bed (narrow)	0.42	0.18
six-row bed	0.40	0.18
full field	0.31	0.17
$LSD_{0.05}$	0.08	0.06
means for pruning regime		
slender spindle		
winter	0.56	0.28
winter + summer	0.41	0.21
North-Holland spindle		
winter	0.29	0.16
winter + summer	0.40	0.19

Interaction occurred between pruning regime and tree shape with respect to bienniality ($P<0.01$). Summer pruning decreased the biennial effect with the slender spindle, yet increased it with the North-Holland spindle (Table 6.3). For both pruning regimes, however, the North-Holland spindle was less biennial than the slender spindle. The single row and three-row beds alternated more than the other arrangements for the slender spindle. The planting system did not affect the bienniality intensity of the North-Holland spindle.

Flowering

The number of flower buds varied strongly between successive years, which is quite common for a biennial cultivar like 'Red Boskoop'. Because the statistical effect of this variability can be avoided by taking the means of pairs of successive years, data were averaged for two pairs of consecutive years, viz. the fifth/sixth and seventh/eighth growing seasons (Table 6.2). Because of interaction between the slender and the North-Holland spindle, the relevant data were analysed separately. Since the variation between treatments applied to the slender spindle was high and even significantly higher than for the North-Holland spindle (at P=0.05), no influence of planting system could be detected. For the North-Holland spindle, the wide three-row bed had significantly fewer flower buds per ha than the other systems. The number of buds on trees of this shape increased with planting density. On average for all planting systems the slender spindle had more flower buds than the North-Holland spindle. Summer pruning decreased the number of buds of the slender spindle from 545 to 512 x 10^3 per ha (at P=0.10, LSD=30) but increased that for the North-Holland spindle from 422 to 443 x 10^3 (at P=0.10, LSD=19).

The effects of summer pruning and tree shape on bienniality were in close agreement with those on yield (Table 6.3); the flowering values exceeded those for the yield. It could also be noted that flowering in the narrow three-row bed alternated more than in the other arrangements, whereas the reverse was found for the full-field system, averaged for both spindle types.

6.4 Discussion

Since in the present trial planting density was dependent on planting system, the effects of these two factors on growth, yield, and flowering could not be assessed separately except for the three-row systems. However, results of other trials have shown that in this respect density is often more important than planting system (Wertheim, 1983).

The basal area of the trunk was taken as a measure of vegetative growth. The strong relationship between trunk girth and dry weight of the vegetative tree parts has been demonstrated by Moore (1978). The trunk could be considered as a good estimator for tree growth in the present trial if there were no interaction between planting system, tree shape, and trunk growth, and the results gave no indications of such interactions. However, the finding that summer pruning affects trunk girth rather than shoot growth in mature trees (Mika, 1986), raises doubts as to whether the trunk is a good indicator of shoot growth for the comparison of dormant pruning and additional summer pruning.

Trunk growth was negatively related to planting density, confirming the reports by Verheij (1972) and Wertheim (1985), and this effect can be attributed to enhanced inter-tree competition. The trunks of the single-row trees in the current trial became distinctly thicker than those in the other systems. This is only partially attributable to lower density (Equation 6.1). Competition for light resources might play a role, being less in the single row than in the multi-row systems, where shading of adjacent trees will reduce growth (Jackson and Palmer, 1977).

The North-Holland spindle grew less than the slender spindle, even at the same tree density (Table 6.2). This may be attributed to the more severe pruning of this tree shape, which requires the removal of many current-year shoots. Cropping, which was double that of the slender spindle, on a per-tree volume basis, may also have weakened growth.

Taylor and Ferree (1984b) found that pruning time affected the degree of shoot-growth reduction, but had no influence on trunk increment. Thus, comparison of pruning times with respect to trunk growth is not relevant, since only pruning intensity plays a role. In the current trial, summer-pruned trees could be considered simply as more intensively pruned than those pruned only in the dormant season, the time of pruning being less important. Saure (1985) too, found little difference in growth between winter- and summer-pruned young apple trees, but found a strong correlation with pruning severity. The additional summer pruning weakened vegetative growth in all treatments but did not affect production. These results are consistent with those reported by Taylor and Ferree (1984b) and Rom and Ferree (1984b), and confirm the conclusion that fruits are stronger assimilate sinks than secondary growth regions such as trunks.

Cumulative yield was positively related to planting density (Equations 6.2 and 6.3). Yields increased rapidly in the first four to five years, but even in the eighth growing season the production per ha continues to increase with density for the slender spindle. Thus, under the moderate growing conditions prevailing at Wilhelminadorp, intensification led to higher production levels, and with the slender spindle even in the mature phase. The full-field and the single row systems yielded better than the three-row and six-row beds, where the inner trees lost productive capacity. This tendency was already noted for the sixth growing year (Wertheim et al., 1986), and it too can be attributed to a lower level of inter-tree competition within the single-row systems. Production per ha averaged for all planting systems was similar for both tree shapes, but comparison for the same plant densities showed that the North-Holland spindle produced less (Table 6.2). Therefore, to obtain the same level of production, the North-Holland spindle should be planted at even higher numbers per ha. The general economical implications of such high density plantings are discussed by Goedegebure (1976, 1984), who calculated that an increase of the planting density in a range between 2200 and 4400 trees per ha led to more yield per ha, and that under average growing and climatic conditions the extra investments, mainly because of the greater number of trees, were paid off after five growing seasons. Today orchards can be fully productive after three or four years (Goedegebure, 1987) which will give an even faster pay-off.

Yield efficiency was expressed as production per unit of trunk-basal area. The production per unit of tree volume is also a measure of efficiency, but its usefulness is disputable because tree volume was calculated for tree dimensions only after pruning. Furthermore, this value represents only outer volume, but the area and distribution of leaves and branches within the tree may also be important with respect to yield. The yield per tree volume is nevertheless an indicative value next to yield per unit of trunk-basal area. The efficiency did not alter with density. The slender spindle tended to be more efficient than the North-Holland spindle (Table 6.2). At a given density, the pruning of the North-Holland spindle affected trunk growth distinctly more than yield. Verheij (1972) and Wertheim (1985) reported a decrease in efficiency at higher densities due to stronger pruning, which affected production more than growth. However, their trees differed in volume, whereas those of the current trial were pruned to obtain a uniform volume per tree shape, and care was taken to ensure that the pruning intensity per tree did not increase with density.

The number of flower buds varied strongly from year to year. For the calculations, the effect of this biennial divergence was partially avoided by taking four consecutive years, thus diminishing the effect of alternate bearing, but variation within treatments remained high. Nevertheless, the number of flowers was smaller for the North-Holland spindle than for the slender spindle, which was due to the smaller canopy volume, as well as a more severe pruning regime. Early foliage growth stimulates flowering by shortening the plastochrone (Buban and Faust, 1982), and the negative effect of pruning on flowering is mainly due to a decrease of the spur:shoot ratio (Davis, 1957; Mika et al., 1977). The more severe pruning regime of the North-Holland spindle increases the number of active growing points and extension shoots on the tree, reducing flower-bud formation. In the present trial, the spur:shoot ratio was lower for the North-Holland spindle (data not given). On average, however, the yield per ha equalled that of the slender spindle, which means that fruit set must have been better. This, too, may be associated with pruning, which increases fruit set (Mika, 1986).

Summer pruning led to a remarkable difference in flowering between the two tree shapes. It increased flowering in the North-Holland spindle, but decreased it in the slender spindle. Reduction due to summer pruning is well known, but enhancement is rare (Mika, 1986). The latter effect is possibly related to increased photosynthesis and transpiration in the basal leaves shortly after pruning, as reported by Taylor and Ferree (1981). In this reasoning, the effect would be stronger in the North-Holland spindle. The supply of carbohydrate to buds is unlikely to be critical for flower-bud formation, but a change of the gibberellin:cytokinin balance because of enhanced transpiration might be responsible for the presence in the xylem sap of higher concentration of cytokinins, which promote flower-bud initiation (Luckwill, 1970).

The reduction of flowering of the slender spindle by summer pruning was associated with a lower bienniality. Since the slender spindle had on average more flower clusters and cropped more biennially than the North-Holland spindle, it seems likely to accept that it flowered excessively, and that a decrease of flowering stimulated the regularity of bearing.

Differences in seed content of the fruits, causing hormonal inhibition of flower-bud initiation, might be responsible for the greater irregularity of the slender spindle. However, this is unlikely in the given trial, for pollinators were equally spread over all the treatments. The length of individual branches could also be involved, being positively correlated with the period being 'out of phase' (Davis, 1957; Monselise and Goldschmidt, 1982). Those small trees, however, are usually out of phase as a whole rather than per branch.

7 Production and fruit quality at two latitudes

Summary

In a comparative study, the effect of tree density (2000, 2667, and 4000 trees per ha) and the ratio of between-to-within row distance (1:1, 2:1, and 3:1) on light interception, fruit production, colour and individual fruit weight in The Netherlands (51°30' and 52°0' northern latitude) and Denmark (55°30') was evaluated. For each combination of tree density and rectangularity, trees were pruned at three heights (1.50, 1.88, or 2.25 m). Fruit production over nine years and seasonal incoming radiation between bloom and harvest were 17 and 15% greater at the lower latitude, whereas relative light interception was about the same. The observed results were in agreement with climate-based estimates of potential production as provided by a crop-growth model, when differences between latitudes in actual daily radiation were taken into account. Fruits were smaller and less coloured at the higher latitude. Production was proportional to light interception and increased with tree density, but the amount of well-coloured fruit per ha did not increase with density in later years, when light interception was more than 70% and a large proportion of shade within the canopy was found. Reduction of tree height did not lead to a better light penetration. On the contrary, fruits were more coloured in the taller and more open trees, even at the highest tree densities. Plantings with 1:1 and 2:1 designs intercepted more light and had a more uniform light distribution than 3:1 designs. This led to higher fruit production and better fruit colour. Fruit weight was not influenced by tree density, rectangularity, or tree height.

7.1 Introduction

For apple, an adequate distribution of light is a very important factor for yield and aspects of fruit quality, such as size and colour. The production of good-quality fruit is therefore a function of absorbed light up to a certain level, which is followed by a plateau or decrease (Jackson, 1989a). Empirical data have shown that apple yield can increase with light interception up to at least

70% of the available light. Interception values higher than about 80% are rarely found (Wertheim et al., 1986; Palmer et al., 1992).

Light interception is a function of leaf area and the spatial distribution of leaves, determined by canopy geometry. Higher tree densities can lead to increased light interception through a greater leaf area and a more even distribution of light (Palmer, 1989a; Palmer et al., 1992). Furthermore, a decreasing ratio of between-to-within row spacing (rectangularity) can increase light interception and give a more uniform light distribution, resulting in higher yields of good quality (Cripps et al., 1975; Vittrup Christensen, 1979). On the other hand, lateral illumination in narrow spacings may be less than that in wider-spaced rows, leading to a lower production (Wagenmakers, 1989a). This problem can be met by manipulation of tree height in relation to alley width (Jackson and Palmer, 1972). The optimum tree height will be lower at higher latitudes with a lower solar elevation. An approach via the optimum tree density, it will make it necessary to investigate the interactive effects of rectangularity and height. The present experiment was performed to quantify effects of these geometrical factors on light interception and distribution, in relation to aspects of apple yield. The influence of available light on production has been assessed in orchards at two different latitudes and results have been used to validate a simulation model on potential fruit production.

7.2 Materials and methods

Orchard design

In the spring of 1983, a trial with three densities (2000, 2667, and 4000 trees per ha) was established, using one-year-old feathered 'Elstar' apple trees on M.9 rootstock at three sites: Wilhelminadorp ('Wi', Netherlands, 51°30' latitude), Werkhoven ('We', Netherlands, 52°0'), and Aarslev ('Aa', Denmark, 55°30'). 'Golden Delicious' was interplanted as pollinizer. All trees had been raised at the same nursery. Each density was planted in three rectangularities (inter:intra-row distances 1:1, 2:1, and 3:1); at each rectangularity three tree heights were realized (1.50, 1.88, and 2.25 m after winter pruning). In all 1:1 and 2:1 plots at 4000 trees per ha, free paths 0.5 m wide were made by winter pruning. The other systems had alleyways giving 1.50 m free space. The soil was overall treated with herbicides to avoid differences in competition with grass or herbs between treatments. Trees were trickle-irrigated in the first years. Tree training was about the same at all sites. Final tree dimensions were dependent on spacing. Rows were oriented approximately

N-S. Three to four rows per plot with an average length of 9 m were planted. The 27 treatments were arranged according to a randomized design at Aa. At the other sites, a split-plot design was used with height and arrangement randomly allocated on the main plots, and tree density on the split plots. At Wi, the experiment was repeated in two blocks, as against one each at Aa and We. Data was subjected to analysis of variance for a factorial experiment. Significant F tests ($P<0.05$) were followed by an LSD test for pairwise comparisons between treatment means. When no relevant interactions occurred, data were combined. The statistical package Genstat 5 release 2.2 was used to perform the analyses.

Fruit production and leaf area

Fruit number and fresh fruit weight per tree were recorded from 1985 to 1992 (1989 at We) for 5 to 8 trees of the central row(s). Fruits were graded at Wi and Aa according to the following classes: 0–10, 10–33, 33–50 (10–50 for Aa) and >50% red-coloured.

Leaf area was calculated by counting all leaves on one or two central tree(s) per plot; each 20th or 25th leaf was picked and its area measured on an image analysis system (Delta-T, Burwell, UK). Leaf area of one tree per plot was determined in all plots in 1986, 1987, and 1988, and of two trees per plot in three plots (1:1, height 1.88, all tree densities) in 1989, 1990, and 1991 at Wi. Leaf records at Aa were made for one tree in all systems in June and September 1987, about 10 days later than at Wi.

Interception of global radiation during the season

Daily records of incoming radiation were done with a pyranometer (CM-11, Kipp and Zn, Delft, spectral sensitivity 305–2800 nm, recording every 12 s) at Aa and Wi. The seasonal pattern of intercepted radiation was measured in the centre of one plot (2667 trees per ha, 1:1, height 1.88 m) with 12 tube solarimeters (Delta-T, Burwell, UK, length 1 m, sensitivity range 350–2500 nm), between 1988 and 1992 from March to November at Wi. The tubes were mounted horizontally in four series of three units placed in line normal to the row direction, at heights of 0.15 and 1 m above the ground, from the centre of one pathway to the next. One line passed through the trunk centre, the other halfway between two adjacent trunks in a row. Data was collected at 1-min intervals for three successive days every two to three weeks. The means for each 10 min were stored, using a Campbell 21X data logger (Campbell Scientific, Inc., Logan, Utah). Percentages of intercepted radiation for a given height were calculated on a daily basis. The meters were calibrated against the Kipp pyranometer in the field for two or three days every two to three weeks.

Light interception and distribution per planting system

Light distribution was measured instantaneously in all systems on days of uniform diffuse light with a cosine-corrected silicon cell (sensitivity range 465–645 nm, Technical and Physical Engineering Research Service, Wageningen). In two replicates per plot, readings were taken at ground level at 25-cm intervals along cross-row lines from the centre of one alleyway to the next, passing the row at the tree centre and halfway between two adjacent trees on a row. Another cell recorded incoming light above the canopy approximately every 30 seconds. Records were displayed on an analogue voltmeter. Horizontal light distribution was calculated by averaging data on percentage light transmission in the direction of the row. Canopy light interception was calculated from the average values of light transmission. Measurements were taken at Aa and Wi between June and September in 1987, 1988, 1990, and 1992 once or twice per year.

In 1989 and 1991 at Wi, light transmission within the crown was measured for all tree densities in 1:1 plots with intermediate tree height. Data were taken along a line centred on the trunk from the north, east, south, and west sides of the crown at levels between 25 and 200 cm above the soil, always at 25-cm intervals. The cells were the same as described above and here, too, measurements were done under diffuse light conditions.

Simulation of potential production per latitude

Potential production of dry matter per latitude was theoretically quantified by using the general simulation model for carbon production as developed by Spitters et al. (1989; Chapter 3). Seasonal crop assimilation was calculated from absorbed light on basis of a daily interval, using actual daily radiation data for Aa and Wi between 1986 and 1992. Gross photosynthesis was based on the non-linear response to light, using maximum values found for apple (Avery, 1977). Daily crop assimilation was obtained by integrating assimilation rates over horizontal leaf layers and over the day using the 3-point Gaussian integration method. For respiration, a fixed value of 40% of gross photosynthesis was used during the entire growing season. The (sigmoid) pattern of leaf growth during the season was assumed to be similar at Wi and Aa. Leaf growth started two weeks before full bloom and maximum leaf area was reached two months later. By assuming that the canopy was homogeneous, any effect of planting system or tree density on light absorption was not taken into account. Light extinction within the canopy followed an exponential pattern according to Beer's Law:

$$I = I_0 \exp(-k\ LAI)$$

where k represents the extinction coefficient, with typical values for direct and diffuse light, and LAI is the orchard leaf area index. Leaf inclination was assumed to be spherical.

7.3 Results

Growing season

Full bloom (80% open flowers) was advanced by 3–4 weeks at Wi relative to Aa. Because the difference was only 2 weeks at harvest, the time between bloom and harvest was slightly longer at Wi. Total incoming radiation between bloom and harvest at Wi exceeded that of Aa by on average 15% (Table 7.1).

Table 7.1

Dates of full bloom, harvest, and level of incoming radiation between bloom and harvest at Wi and Aa.

year	full bloom		harvest		radiation (MJ/m^2)	
	Wi	Aa	Wi	Aa	Wi	Aa
1986	20 May	3 Jun.	25 Sep.	13 Oct.	2252	1906
1987	11 May	10 Jun.	24 Sep.	31 Oct.	2097	1887
1988	4 May	26 May	20 Sep.	27 Sep.	2185	1942
1989	3 May	18 May	6 Sep.	22 Sep.	2487	2107
1990	16 Apr.	8 May	4 Sep.	20 Sep.	2595	2350
1991	29 Apr.	5 Jun.	3 Oct.	14 Oct.	2431	1953
1992	24 Apr.	23 May	11 Sep.	23 Sep.	2486	2263
mean	2 May	27 May	18 Sep.	4 Oct.	2362	2058

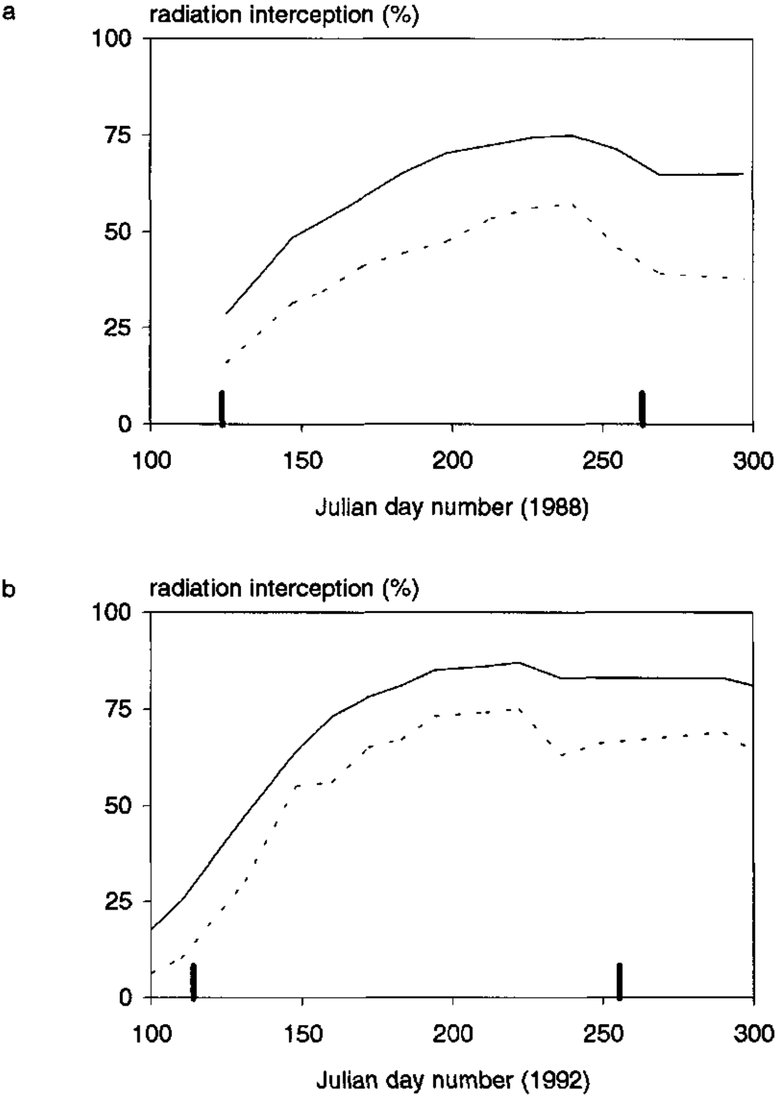


Figure 7.1

Seasonal interception of radiation at ground (solid lines) and 1 m above the ground (broken lines) in 1987 (a) and 1992 (b) at Wi. Bars indicate dates of full bloom and harvest.

Seasonal pattern of intercepted radiation

As illustrated in Figure 7.1 for 1988 and 1992, the percentage of intercepted radiation at Wi increased gradually as the season progressed, reaching a maximum level two months after bloom, between 21 June and 15 July (Julian day 172–196), when leaf growth was completed. The general patterns in all years were similar, but interception was greater in later years. Of course, values at the ground were higher than within the canopy. Averaged for all years, 48% of radiation was intercepted halfway down and 66% under the trees. The decrease in interception some weeks before harvest was due to summer pruning. After harvest, values remained constant. Marked leaf fall did not occur until the end of October.

Light interception and distribution of planting systems

For the various planting systems, light interception in June was slightly lower than in July or later, and mean values were greater in later years, but the effect of the different factors was the same. Therefore, in Table 7.2 only data on maximum light interception are presented for two seasons. Light interception did not differ significantly between Aa and Wi and increased with tree density, the differences being greater in 1987 than in 1992. The increase of light interception with decreasing rectangularity was evident. Moreover, the effect of rectangularity increased markedly with orchard age. Finally, the largest differences in light interception were

Table 7.2

Diffuse light interception (%) as affected by planting density, tree arrangement, and tree height, July–September 1987 and 1992, averaged for Aa and Wi. Mean data are given where no interaction occurs.

	diffuse light interception (%)		
	1987	1992	1987/1992
trees/ha			
2000	51.0	67.9	
2667	59.6	73.7	
4000	70.7	83.8	
F-test	*'		
$LSD_{0.05}$	2.4		
arrangement			
1:1	63.6	81.3	
2:1	60.4	74.6	
3:1	57.3	69.6	
F-test	***'		
$LSD_{0.05}$	2.4		
height			
2.25			68.9
1.88			67.0
1.50			67.4
F-test			NS
$LSD_{0.05}$			-

' significant interaction with year
NS, *, **, *** non-significant or significant at $P<0.05$, 0.01, or 0.001, respectively.

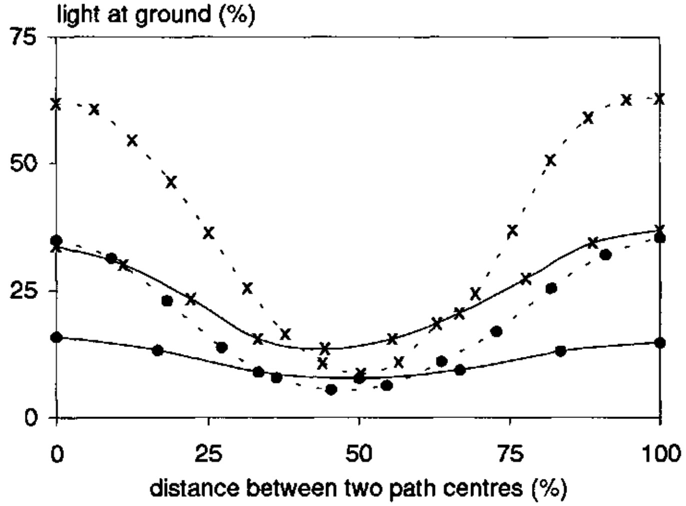


Figure 7.2

Patterns of light transmission at the ground in 1992, expressed as percentages of incoming light, at 2000 (marked with asterisk) and 4000 (dots) trees per ha, each at rectangularities 1:1 (solid lines) and 3:1 (broken lines), averaged for three tree heights, and for Wi and Aa.

found between the lowest density with 3:1 designs (61%) and the highest density with 1:1 designs (89%). The effect of tree height was not significant.

Light distribution was more uniform at higher densities and lower rectangularities (Figure 7.2). The smallest difference in light transmission at the ground between row centre and alley centre was measured in the 1:1 plantings at the highest tree density. Although the levels of light transmission differed between measurements early and late in the season and between years, the patterns were roughly the same (data not shown). Because the effect of tree height was only slight, data were averaged for the given tree heights. Light penetration to the alley centre was about the same for the 1:1 designs at the lowest density and the 3:1 designs at the highest density.

Light distribution within the crown

As shown for the lowest and highest density in Table 7.3, light penetration within the crown decreased rapidly from top to bottom and from outer to inner side. The density of 2667 trees per ha occupied an intermediate position.

At all densities, less than 30% of the incoming light was measured at a distance of 0.5 m from the outside of the crown. The shaded crown volume increased with canopy light interception. The latter was 71, 82, and 91% at 2000, 2667 and 4000 trees per ha, respectively.

Table 7.3

Light transmission as percentage of incoming diffuse light within tree crown at two planting densities (1:1 arrangements, tree height 1.88 m) at Wi, averaged for N-, E-, S-, and W-range, and for August 1989 and July 1991.

height from ground (cm)	*2000 trees/ha*					*4000 trees/ha*			
	distance from tree centre (cm)								
	0	25	50	75	100	0	25	50	75
175	48	66				46	55		
150	26	43				20	37		
125	18	28	57			16	28		
100	13	23	45			10	17	35	
75	6	8	21	47		5	8	18	
50	4	5	8	23	43	4	5	9	
25	5	5	9	20	33	6	6	10	12

Leaf area index

The LAI was greater at the lower latitude. Mean LAI in September 1987 (June between parentheses) was 2.2 (1.3) and 2.7 (1.7) at Aa and Wi, respectively. LAI was proportional to planting density (Table 7.4), but there was no clear effect of arrangement and tree height. According to data for 1986 and 1987, LAI at 3 and 4 weeks after full bloom was already 58 and 64% of the maximum. Mean LAI of the 1:1 plots with intermediate tree heights at Wi increased from 1.8 in 1986 to 4.3 in 1991.

The fraction of canopy light interception (f) appeared to be an exponential function of LAI following

$$f = 1 - \exp(-0.116 - 0.37\,\mathrm{LAI}) \qquad (r^2 = 71.5,\ n = 172)$$

with standard errors of constant and slope being 0.04 and 0.02, respectively (Figure 7.3). Because LAI values exceeding 4 were not observed at Aa, a separate fit for Aa of an exponential curve in Figure 7.3 was not useful. LAI values greater than 3 to 4 increased light interception relatively little.

Table 7.4

Orchard LAI at Wi early (June) and late (July–September) for 1986–1988 (all plots) and for 1989–1991 (late, only 1:1 arrangements, 1.88 m high trees).

trees/ha	1986 early	1986 late	1987 early	1987 late	1988 early	mean 1986–1988	1989	1990	1991	mean 1989–1991
2000	1.0	1.5	1.3	2.0	1.7	1.5	2.9	2.5	3.5	3.0
2667	1.3	2.1	1.5	2.4	1.9	1.8	3.2	3.4	4.3	3.6
4000	1.6	3.1	2.2	3.4	2.6	2.5	4.6	3.2	5.0	4.3
F-test						***				
$LSD_{0.05}$						0.2				

NS, *, **, *** non-significant or significant at P<0.05, 0.01, or 0.001, respectively.

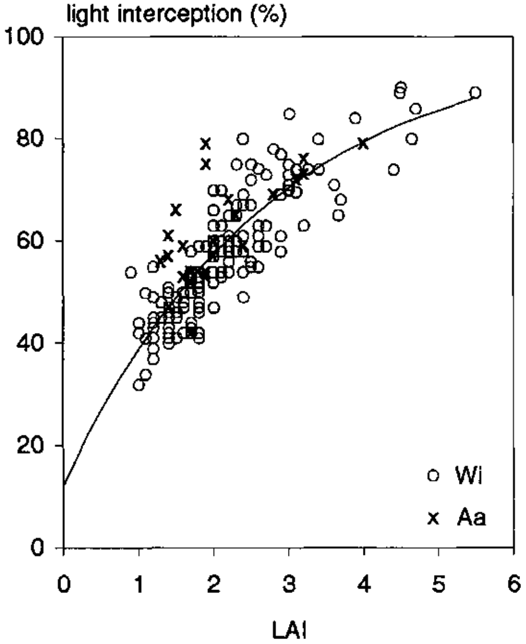


Figure 7.3

Relationship between LAI and canopy light interception at Aa (1987) and Wi (1986–1991). The regression line applies to data of Aa and Wi.

Fruit production

Trees produced fruit from the second year after planting. Cumulative yield per ha at We (1984–1989) was 6% less than that at Wi. At Aa, yield was 9% lower than that at Wi over the first six years. Between 1989 and 1992, trees at Aa even produced 12% per year less than those at Wi (Table 7.5).

Table 7.5

Cumulative fruit production (tonnes per ha) per location and planting system between 1984–1989 and 1989–1992. Mean data are given where no interaction occurs.

	1984–1989			1989–1992
trees/ha	1:1	2:1	3:1	
2000	164	166	155	162
2667	200	181	184	177
4000	243	233	204	187
F-test		**'		***
$LSD_{0.05}$		14		10

arrangement	1989–1992
1:1	183
2:1	182
3:1	161
F-test	***
$LSD_{0.05}$	10

	1984–1989			1989–1992
height	Wi	We	Aa	
2.25	202	200	194	196
1.88	198	199	173	168
1.50	199	168	176	161
F-test		**'		***
$LSD_{0.05}$	12	16	16	10

location	1984–1989	1989–1992
Wi	200	182
We	189	
Aa	181	161
F-test	***	***
$LSD_{0.05}$	9	9

' significant interaction

NS, *, **, *** *non-significant or significant at P<0.05, 0.01, or 0.001, respectively.*

Production increased with planting density. For example, in the period 1984–1992 at Wi, trees at density 4000 per ha produced 35% more than those at 2000. The average increase in yield between densities was considerably greater in the earlier years (Table 7.5). Production increased with decreasing rectangularity, too. Although in the later years no interaction between density and arrangement could be found, this was noticed for the period 1984–1989. The difference in yield between densities was larger on

1:1 and 2:1 than that on 3:1 designs. At the lowest density, differences between arrangements were, however, not significant. In general, the taller trees produced more, although the effect of tree height was not observed at Wi in the period 1984–1989.

Cumulative yield (1984–1992) was positively correlated with final light interception in 1992, but the variation was large (Figure 7.4). This was partly due to the different tree densities and rectangularities, leading to different patterns of light distribution. The more uniform light distribution at lower rectangularities or higher densities favoured production as long as light availability within the canopy was adequate.

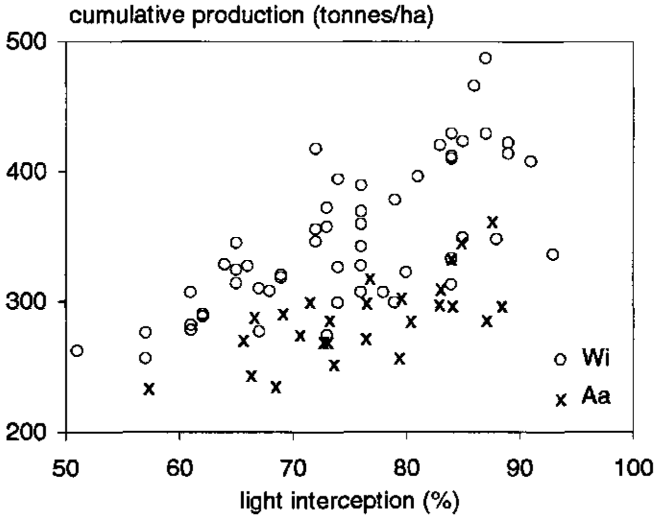


Figure 7.4

Cumulative yield (1984–1992) and final light interception (1992) at Aa and Wi.

Fruit weight and colour

Fruits were markedly smaller at the higher latitude. Mean fruit weight at Aa was 123 g against 165 g at Wi and We. The lower weight of fruits at Aa was associated with a 25% higher fruit number per tree between 1986 and 1992 and half the leaf area per fruit in 1987, compared with Wi. Even at a given fruit number or leaf-fruit ratio, however, fruits were smaller at Aa than at Wi (data not shown). The effect of tree density and rectangularity on fruit weight was not significant. Tree height had a small effect. At the tree height of 1.50 m, fruit weight exceeded that of taller trees by only 10 g.

Fruit colour at Aa was poor. The production of well-coloured fruit (more than 50% red blush) was only 40% of that at Wi (Table 7.6).

Table 7.6

Production (tonnes/ha) of fruit with more than 50% red blush, averaged for 1990–1992, at Wi and Aa per planting system.

trees/ha	Wi	Aa
2000	18.4	8.6
2667	20.3	8.4
4000	19.7	6.2
F-test	**	NS
LSD	1.2	
height (m)	Wi	Aa
2.25	23.4	8.6
1.88	19.4	7.0
1.50	15.5	7.6
F-test	***	NS
LSD	2.2	-
arrangement	Wi	Aa
1:1	21.7	8.1
2:1	20.8	8.5
3:1	16.0	6.6
F-test	***	NS
LSD	1.2	
year	Wi	Aa
1990	14.8	2.5
1991	20.5	6.0
1992	23.0	14.7
F-test	***	***
LSD	1.9	1.4

NS, *, **, *** non-significant or significant at $P<0.05$, 0.01, or 0.001, respectively.

Unlike total production, the production of well-coloured fruit was not proportional to tree density. At both locations, the largest production of well-coloured fruit per ha was reached by the highest trees in 1:1 or 2:1 arrangements. Measurements at Wi indicated that the upper tree half only had slightly more fruits than the lower half, but the proportion well-coloured fruit was much higher for the upper part. The effect of density and rectangularity was more evident for the lower than for the upper part (data not shown).

Simulation of potential production

Table 7.7 illustrates the calculated mean, minimum, and maximum values of potential production at Aa and Wi per season for LAI values between 2 and 3. At the same LAI, the expected average production at Wi would be 18% higher than that at Aa. Production can be 10–15% higher than average in sunny, early seasons but 6–9% lower in late seasons with less sunshine. A reduced leaf growth at the higher latitude is an additional factor that increases the differences between locations. Thus, for LAI 2 and 2.5 at Aa and Wi, respectively, the average production at Aa would be 26% lower than that at Wi. This difference would be slightly smaller at higher LAI values.

Table 7.7

Mean, minimum and maximum values of simulated production of total dry-matter (tonnes/ha fruit, leaves and woody biomass) at Wi and Aa for LAI values between 2 and 3, on the basis of absorption of daily radiation between leaf emergence and harvest, calculated for the individual years between 1986 and 1992.

			final LAI		
site	dry matter (tonnes/ha)		2.0	2.5	3.0
Aa	mean	(1986–1992)	16.6	18.9	20.7
	minimum	(1986)	15.7	17.9	19.5
	maximum	(1990)	19.3	21.9	24.0
Wi	mean	(1986–1992)	19.6	22.3	24.4
	minimum	(1987)	17.9	20.4	22.3
	maximum	(1990)	21.6	24.5	26.8

If it is assumed that 55% of the assimilates was allocated to fruit (Wagenmakers, 1993), fruit dry-matter content would have been 17%, and LAI values between 2 and 3, mean fruit production could be 54 to 67 at Aa, and 63 to 79 tonnes per ha at Wi.

7.4 Discussion

In general, the effects of orchard geometry did not interact with latitude. Therefore, the factors are discussed separately.

Influence of latitude

The differences in incoming radiation between bloom and harvest at Aa and Wi were largely due to latitude (Chapter 3). The 15% higher incoming radiation led to 17% higher fruit production at Wi between 1984 and 1992. Similarly, Heim et al. (1979) found 24% more radiation and 25% more dry-matter production for apples grown in France (43° latitude) than in England (51°) at a given crop load. On the basis of light absorption and gross photosynthesis, the model used in the present study predicted that potential differences in fruit yield between the two sites were about 10 tonnes per ha, which is only slightly more than was found empirically. This overestimation by the model is partly due to the too simplified assumption of uniform leaf distribution. Although the mean relationship between radiation and yield can be useful to estimate yield, it cannot be applied to canopies differing in crop load, for Heim et al. (1979) reported that fruit number per leaf area determined dry-matter partitioning more than any climatic factor did. The finding that differences in yield in the initial years between Aa and Wi were smaller than calculated may also be explained by the higher number of flowers or fruit per tree at Aa (Callesen and Wagenmakers, 1989).

Lower light inputs at the higher latitude led to a smaller fruit size at a given crop load. This effect was probably intensified even more by the high cropping level at Aa (Lakso et al., 1989b). Forshey (1990) even found that a heavy crop load reduced fruit growth in the succeeding year. Furthermore, a negative factor for fruit size may be the lower temperature at the higher latitude (Reichel and Schmidt, 1986). A similar difference of fruit size between latitudes was found for apples grown in Italy (45° latitude) and England (51°) (Palmer et al., 1989).

Differences in the production of well-coloured fruits between the two latitudes were larger than those in total yield. The higher crop load at Aa will have been responsible for less well-coloured fruit (Saure, 1990). Even when crop load was low, however, fruit colour remained poorer at Aa. This could be due to the very low light levels in the end of the season, when differences between latitudes are much larger than on average for the entire growing season. Fruit-colour formation is much more sensitive to light conditions than fruit growth is (Jackson et al., 1971).

Influence of orchard geometry

By relating yield to inter-row and intra-row spacing, Berry (1967) showed that the highest light interception and yield should be achieved by 1:1 arrangements. This is generally confirmed by the present results. Differences in yield between 1:1 and 2:1 were, however, very small in later years, despite differences in light interception. Yield increased with planting density, too, but the production of well-coloured fruit in later years was the same for all densities. It should be realized that most of the final values of light interception were above 70%, which was achieved by LAI values exceeding 3 (Figure 7.3). Verheij and Verwer (1973) already reported that more than 70% light interception might be suboptimal, as has been confirmed by theoretical calculations on row systems (Wagenmakers, 1991c). Values of light interception above 70% only enlarged the shaded crown volume. The higher leaf density occurring at the higher tree densities, which was also observed by

Palmer et al. (1992), may have strengthened negative effects of shading even more.

Fruits are generally smaller at higher tree densities, which could be due to a higher fruit number per leaf area (sink strength) or reduced light exposure, affecting carbohydrate supply (Tustin et al., 1989). Fruit weight was, however, the same at all densities in the present trial. This was partly due to the fact that sink strength did not change with density. Because a substantial LAI was already produced early in the season, the carbohydrate supply also was probably not limiting. The values of leaf area per fruit exceeded 1000 cm^2 at Wi. Minimum values necessary to provide sufficient assimilates for Elstar fruits (165 g) were found to be between 400 and 800 cm^2 leaf per fruit (Hansen and Stoyanov, 1972). Wertheim (1978) confirmed that fruit size was not affected by tree density under conditions of abundant leaf development.

Since LAI was similar, the taller trees had a more open structure and a lower leaf density than lower trees did. Such a spatial distribution of leaves favoured light penetration within the tree and reduced differences in light interception between tree heights, compared with trees having the same leaf density among different heights (Wagenmakers, 1991c). Consequently, 2.25-m high trees produced not only more, but even better coloured fruit than shorter trees, even at the narrowest spacings. Callesen (1993) also reported little difference in light interception but a higher production of apple hedgerows ranging in height between 1.75 and 3.75 m. Tombesi and Belleggia (1986) confirmed for peach that not only colour, but also fruit size and sugar content improved on trees with a lower leaf density.

To conclude, the most efficient way of increasing the production of well-coloured fruit is provided by a system with a uniform spatial distribution of trees and a low degree of leaf clustering. Both factors will lead to a strong and efficient interception of light. The advantage of uniform light distribution is associated with the non-linear photosynthetic response to light. Such an optimum distribution of spatial elements can be achieved by reducing the rectangularity of planting and by using training systems to produce tall but slender trees. Production can also be increased by a higher tree density, which is largely due to increased LAI. When at the same time leaf density increases, however, the production of well-coloured fruit might be affected negatively, as a result of a disproportional increase in shaded crown volume.

8 General discussion

The direct relationship between fruit production and light interception, demonstrated by many authors, underlines the importance of optimizing light interception. The present study has provided a quantitative description of the relationship between light and orchard configuration. A mathematical model was developed to discriminate between density, arrangement, tree size, and tree shape. Empirical data were used to validate the model, and to convert effects of light interception into production and fruit quality.

Light interception can be considered as an objective way of evaluating planting systems and, furthermore, is easy to measure. Light interception is therefore the key factor for the comparison of systems productivity (Palmer, 1993). Modelling of light interception is useful for reaching strategic decisions on the planting of trees. The measurement of light interception in individual systems can be helpful for growers in making observations on canopy development. The results may provide valuable information as to whether the optimal level of light interception is reached, or even surpassed. If necessary, pruning and training can be adapted. Recently, Dutch advisers have started light measurements in commercial orchards to obtain objective support for recommendations on tree management.

8.1 Importance of light

Potential production

An attempt has been made to provide a general model for potential apple production in different regions (Chapter 3). Latitude has been used as the basic variable, but climatic differences can of course be very great between regions at a given latitude. Altitude and distance to large open-water areas strongly control variations in climate. This report therefore concerns primarily a research study, elucidating effects of light and temperature and giving insight into the cultural limits of different apple cultivars. As a further step, this model on primary production should be integrated into models evaluating the potentiality of fruit growing as restricted by other factors, such as the availability of water (van Lanen et al., 1992). Unfortunately, little has been published on potential fruit growing. The present model may serve as a basis to verify the optimum growing region for individual cultivars.

The estimated level of potential production is rarely achieved, perhaps partially due to a reduction of photosynthetic capacity of the leaves. For well-managed orchards, only a slight reduction of photosynthesis can be anticipated. In many other orchards, however, leaf photosynthesis is reduced to some extent by a low nitrogen content of the leaves, the occurrence of abiotic stress, or diseases and pests. Stress may also lead to leaf drop, thus reducing canopy photosynthesis. The reduction of canopy photosynthesis will have a direct effect on current year's fruit production, but may also interfere in flower-bud formation or in the formation of reserves and hence production of the following year. In a lysimeter experiment, leaf area, flower number per tree, fruit set, and fruit yield were reduced by long-term water stress. Obviously, trees adapt to low water supply by reducing growth (Sritharan and Lenz, 1988).

The present model assumed a similar photosynthetic capacity for all leaves. Shaded leaves will, however, have a lower maximum photosynthetic rate and light saturation point. A morphological effect is possibly involved here, since on a dry-weight basis the maximum photosynthetic rate does not differ between shaded and exposed leaves (Rom, 1991).

Actual production is reduced by clustering of leaves within row systems. Calculations have shown that this reduction can be considerable (Chapter 5). Integration of the general crop growth model into the model of light interception by planting systems should be the next step in modelling potential yield of orchards.

Dry-matter distribution

Fruit production is determined by the allocation of dry matter over the different tree components. Assimilate allocation is primarily regulated by internal mechanisms, such as competing sinks. The larger the sink, the greater its share of assimilates. Sink size is important in the competition between shoots and fruits in the early part of the season. The competition between fruits and roots, later in the season, may also be related to differences in vascular resistances (Evans, 1990).

In general, the influence of light on the distribution of assimilates is small. Light only affects the partitioning of assimilates at critically high levels of shading. The sensitivity to shade, however, may differ between cultivars. Preliminary results indicated that in Fiesta the percentage dry matter incorporated into fruits was reduced by about 20% when more than 75% light was intercepted at two months after full bloom, whereas dry-matter distribution in Jonagold in the same experiment was not affected at all (Wagenmakers and Tazelaar, 1994). The first weeks after bloom are critical. Byers et al. (1991) found that only a few days of heavy shading (8% of light) between 2 and 4 weeks after full bloom induced 95% fruit abscission. They could not find any effect on fruit drop when shade was applied some weeks earlier or later. They considered excessive but not unrealistic shading levels. The growth rate of individual fruits is also sensitive to shade. Lakso and Corelli Grappadelli (1992) reported an immediate reduction of fruit-growth rate by 30% at moderate shading levels (35% transmission) at 4 weeks after bloom. The smaller fruit size persisted until harvest. In their experiment, fruit growth rate was again sensitive to shade late in the season, indicating that carbon demand dominated supply. Calculations reported in Chapter 3 have confirmed that respiration increased in proportion to photosynthesis at the end of the season. It is therefore recommended that studies on potential fruit production should include not only day-to-day variation in light, but also the susceptibility to weather in certain stages of fruit development.

Generally, an effect of density, arrangement, or tree height on dry-matter distribution has not been observed (Archbold et al., 1987; Wagenmakers, 1993). Robinson et al. (1993) showed high efficiencies of Y-trellis systems and slender spindles compared with wider-spaced, larger central-leader trees. It should be kept in mind, however, that in their experiment the systems having a higher efficiency were planted on a more strongly dwarfing rootstock, which in itself must have favoured fruit production. This higher efficiency was probably primarily an effect of the used rootstock. Avery (1969) found even for young, well-illuminated trees, that the dwarfing rootstock M.9 had fewer growing points, stopped shoot growth one month earlier, and allocated less dry matter to the roots than the invigorating M.16 did.

8.2 Modelling light interception by planting systems

The analytical work on light distribution has led to progress in the understanding of the performance and production capacity of different orchard systems. As such, discussions that could be dominated by prejudices can now be rationalized on the basis of a better quantitative understanding of what really happens. The utility of the model has been shown in that it reduced the number of ad hoc experiments and stimulated new experimental approaches, such as looking for practical applications of a planting system with a low rectangularity. The estimations on minimum plot size and number of guard trees or rows are useful in the designing of experiments. If used with caution, the model results may provide indications about the optimum planting density. Optimum planting density is, however, strongly dependent on planting system, tree height, and leaf density. If leaf density and rectangularity do not increase, a higher light interception and better light distribution can indeed be expected from higher planting densities. On the other hand, if leaf density or rectangularity proves to increase, the effect of a higher planting density will be small or even negative.

Knowledge of leaf and light distribution within trees is essential to the obtaining of insight into the physiological processes controlling production and dry-matter distribution. Measurements on leaf and light distribution within the tree are, however, complicated and time-consuming. Instead, models that describe light transfer through individual trees may be used. For verification of a model, only a limited set of measurements is needed. The present model on light distribution has been shown to be sufficient for a variety of planting systems. Further refinement with respect to leaf distribution within the crown would certainly be useful, but probably not necessary if the main point is the comparison of light distribution in different systems rather than the prediction of actual behaviour.

8.3 Modelling fruit production

For the economic product, not only the total production per ha, but also the variation in quality aspects between individual fruits is important. It should be kept in mind that price differences between fruits of different grading groups are very large. Even for fruits in the highest quality class, prices can differ by more than 25%. The item of uniformity scores high. In the present situation, the light-interception model may provide basic information on minimum light levels within trees required to obtain a given grade of fruit. Additional experimental work remains to be done on typical relationships between light and fruit quality. To estimate the within-tree variation in fruit quality more accurately, the influence of light on individual fruit growth and development throughout the season should be quantified. Considering the importance of temperature for the growth, development, and ripening of the fruit, it might be worthwhile to study the effect of temperature in different locations within the canopy as well (Palmer, 1993).

Climate chambers suitable for trees should be employed to clarify the physiology of the fruiting process, but their use is, unfortunately, very expensive. Models enable a more efficient use of empirical data on crop physiology, because they invite the strict formulation of hypotheses on physiological processes that determine the growth and development of the various tree components. An attempt should be made to formulate a hypothesis that explains production and allocation pattern of carbon during the season. The concept of Penning de Vries and van Laar (1982) already provides a basis for simulation of the balance between assimilate production and consumption. Growth will only occur when gross photosynthesis exceeds the maintenance requirements of living tissue. The maintenance respiration demands on carbon urgently need experimental validation.

A certain amount of assimilates will be stored as reserves to meet the needs in the dormant period and in the initial part of the growing season. Much remains to be investigated about the minimum required amount of reserves. In a theoretical approach on the carbon balance of a shoot, Johnson and Lakso (1986) estimated that about 20% of what is needed for growth of an apple shoot was drawn from reserves, the remainder being supplied by current assimilates. As a first assumption, a base level of reserves might be considered, below which maintenance respiration would continue at a reduced rate (Mohren et al., 1990). The driving forces in assimilate allocation patterns, being of crucial importance as they depend on both development stages of the tree and abiotic factors, deserve special interest. Because much is still unknown about the underlying mechanisms, so far the models have to rely on distribution keys describing the order of sink strength in different parts of the season. The effect of temperature on competition between the various sinks should be clarified. For example, it has been found that shoot growth is favoured more by high temperatures shortly after bloom than fruit growth is (Tromp, 1994). In that period, shoots appear to be a stronger sink than fruits. This can lead to increased fruit drop and, consequently, a higher carbon supply of the individual fruit.

8.4 Practical applications

Planting density

Early in the orchard's life, when light penetration within the canopy is sufficient, tree density is the most important orchard factor for light interception. Light interception is, however, not an accurate measure for production in full-grown canopies. In that situation, there is ample light interception but the within-tree light distribution may vary, interfering with qualitative as well as quantitative aspects of fruit production. The critical level of light interception seems to be approximately 70% for apple. The critical interception may be slightly lower for pear. With Conference, the cumulative production over five years has been found to be similar at light interception values between 60 and 85% (Wagenmakers, unpublished data).

The economic result of changes in planting density and planting system strongly depends on the production and price level of the fruit and the planned lifetime of the orchard. For orchards between 2000 and 4000 trees per ha, it has been shown that economic results improved with increasing density (Goedegebure, 1978). In a feasibility study on densities higher than 4000, Goedegebure (1993) expected that a further increase in planting density, up to 12,000 trees per ha, could still lead to better economic results. It has been confirmed that trees at densities of 6000 trees per ha are able to produce more fruit with a high quality than those at 3000 (Wagenmakers et al., 1994). Although total production per ha was found to increase with density even up to 20,000 trees per ha, the share of well-coloured fruit decreased sharply at densities exceeding 10,000 trees per ha, where light interception exceeded 70%. At a light interception of 85% the proportion of fruit without economic value increased even to 25%. It is clear that under these conditions, the high density will be less profitable than traditional orchards.

Observations in commercial orchards have shown that systems with 2000 to 5000 trees per ha can intercept as much light as those with higher densities already in the third year after planting. Still, production per unit light interception was considerably higher for the higher densities (Wagenmakers and Tazelaar, 1994). It should be underlined that cultural practices may have considerable effects. Growth control is an important issue at high densities. Generally, growth control by fruiting will be sufficient but in case of very high densities, growers tend to go for extreme methods of growth reduction and apply root pruning and/or growth retardants. Insufficient growth and inadequate light interception and production may be the result as was actually found in some high-density systems. Too drastic growth restriction should be avoided.

Both the model and the experimental results have emphasized the importance of a low leaf density per unit crown volume. The finding that leaf density may increase with higher planting densities for a given rootstock is in conflict with optimization of light use (Chapter 7). It is, therefore, recommended that for future intensification, rootstocks having lower leaf densities should be used. In The Netherlands, M.9 is currently used as rootstock for a very wide range of densities, but more strongly dwarfing rootstocks such as M.27 and P.22 may be more suitable at higher densities. Cropping trees on M.27 were found to have a leaf density that was only 75% of that on M.9 (S.J. Wertheim, pers. commun., 1993). The relatively small fruit size on M.27, as compared to M.9, may be an advantage for large-fruited triploid cultivars with large fruits, but is a disadvantage for diploid cultivars. Therefore, other rootstocks that have less vigour than M.9 and that do not reduce fruit size are currently being tested.

Planting system

In principle, a square design can be recommended as the optimum arrangement for tree crops but the practical application of full-field square designs depends on the availability of adapted, over-the-row machinery. Van Lookeren Campagne and van de Werken (1984) described a prototype of a mechanized system that could be suitable for spraying, mowing, weed control, and harvesting of apple and pear orchards, arranged in seven-row bed systems with pathways parallel to the alley.

Despite positive economic predictions (Cahn and Goedegebure, 1991), full-field systems at low rectangularities are hardly used. Reasons for hesitations might be found in negative experiences in some full-field orchards, where walking distances from tree to fruit bin at harvest were too long. Furthermore, tree height should be restricted to about 2.25 m for the over-the-row machinery (van Lookeren Campagne and van de Werken, 1984), which may be difficult for taller trees (such as pears). For semi full-field and traditional multi-row beds, there is fear of uncontrolled growth, associated with high shading levels. Although the allotted space per tree is higher in a bed system, it should be emphasized that sufficient light transmission to the central parts is essential. Tree size in bed systems should not be larger than in comparable single rows.

Today, bed systems may be a less attractive option, partly because the area of black soil is usually larger than in single rows using grass strips (Chapter 2). Although restrictions on the amount of soil herbicides have not yet been applied, the recommendation for integrated fruit growing is, to reduce the area of black soil. In some regions (South Tirol), the advice is to keep orchards free from herbs only in spring; there should be no additional spraying in the summer. If the use of herbicides should be banned, mechanical weed control will be easier in single rows.

Tree height

It has been shown that single rows have suboptimal light interception, compared with less rectangular multi-row systems (Chapter 5). As compensation, tree height can be increased to intercept more light. It is precarious to give a general rule of thumb on the relation between tree height and row width because of the interaction with leaf density (Chapter 4). However, with use of the light-interception model as an expert system, some guidelines can be given. Table 8.1 illustrates model results on light interception by two planting systems (single rows and double-row beds with a walking path, 2 m wide, parallel to the alley), each at three crown heights (1.95, 2.45, and 2.95 m) and two within-row distances (1.25 and 0.75 m). The alley width (from trunk to trunk) was 3 m in all systems and leaf density was the same (5 m^2 m^{-3}) for all trees. Under these constraints, light interception increased by about 10% for each 0.5 m of increasing tree height. Trees in single rows should be about 0.5 m taller than those in double rows to achieve similar light interception. The higher planting density of such a system would not lead to more light interception, even if the trees were trained 1 m taller. This is explained by the considerable decrease in canopy volume for the narrower spacing. Light interception should be improved by reducing the alley width as well as the within-row distance, or by planting double-row systems with walking paths.

Table 8.1

Calculated light interception (in % of available diffuse light) of single rows and double rows for within-row tree distances of 1.25 and 0.75 m and tree heights of 1.95, 2.45, and 2.95 m. Row distance is 3 m in all systems, path width of double row is 2 m.

within-row distance	tree height (m)		
(m)	1.95	2.45	2.95
single row			
1.25	49.2	55.1	59.9
0.75	37.9	43.5	48.3
double row			
1.25	53.9	60.2	64.8
0.75	41.3	47.5	52.9

Within certain limits, a taller tree may be an option to increase light interception. An additional advantage of taller trees is that when flowers or fruits are damaged by spring frost, tree tops can still give a reasonable crop in contrast to lower parts. Moreover, regions at lower latitudes may prefer a larger tree to prevent sunburn. There are several agronomic reasons, however, to limit tree height, such as ease of harvesting and avoidance of losses of spray liquid to the environment.

8.5 Future research

Light interception may be used for a first prediction of transpiration. For periods of a week or longer, crop production and transpiration are strongly correlated, being determined by incoming radiation and related to the saturation deficit of the air (de Wit, 1958; Monteith, 1990). This relationship does not apply, however, for shorter periods and does not account for differences in water use efficiency between cultivars. Such characteristics have to be determined empirically or with modelling efforts.

The model on the absorption of global radiation may be used to quantify effects of planting system on transpiration. The present model includes only visible light. To calculate transpiration, the absorption of near-infrared radiation must be taken into account as well and it will be necessary to incorporate reflectance and transmittance of the leaves, since scattering in the near-infrared region is much greater than in the visible region. Scattering by non-horizontal leaves in three-dimensional systems is too complicated to simulate. As an alternative, empirical values of the radiation extinction may be derived (Goudriaan, 1977).

Current estimations on water use by orchards suffer from the lack of reliable information on leaf area. Transpiration is related to an empirical factor, derived from leaf area measurements on young trees (Kodde and Kipp, 1990). These data are insufficient for the prediction of actual leaf area for a given day or orchard. This means that errors in the prediction of transpiration can be large. Transpiration can be underestimated by 50% (van der Maas and Bolding, 1994). A simple model on leaf development as a function of accumulated degree-days over the season (Johnson and Lakso, 1985) may be used to improve the forecasting of transpiration. Predicted leaf area should be calibrated against direct or indirect measurements, the latter by making use of canopy light interception.

Knowledge of leaf area development may also improve spraying efficiency in crop protection. In the recommendations used in The Netherlands, the only distinction made in the quantity of spray liquid per ha is between single rows and multi-row systems, and between very young and older orchards. Differences between three-year-old and older orchards are not taken into account (Anon., 1994, pp. 7–8). Spraying is required quite frequently. Integration of actual leaf area and leaf distribution throughout the season for typical orchards or cultivars in the advice on spraying may lead to a more efficient dosage, thus reducing the amount of fungicides and pesticides.

The flexibility in tree shape and arrangement makes the model on light interception by three-dimensional subcanopies widely applicable to other crops with clustered leaves. The dimensions of the subcanopies are not relevant, and can range from pineapples to oil palms or banana plants. The three-dimensional approach could also be used for row canopies in their early development, when competition with weeds for light is important. Our approach for light distribution under the canopy could be useful for work in forest communities where a minimum of light is required for understorey growth or for recreation, and for that reason may be linked with a general model on forest growth (Mohren et al., 1990). Because experiments on trees last even for decades, models form the basis of research in agroforestry. Validation remains a problem, which is obviously due to the growth rate as well as the size of the trees. Direct measurements on leaf distribution have been done for fruit trees. It is possible to define coefficients on clustering and light extinction for different species. Once a model has been validated for small trees of a given species, the reliability of application to forest communities with larger trees will increase.

The main concern of this thesis was the analysis of light interception of orchard systems and its effects on production and fruit quality. Modelling proved to be useful for explaining the causal relationships between geometrical properties of trees and light interception. The results give an impression of the possibilities for manipulating productivity with orchard systems. As such, the present work could serve as the basis for further analyses on the production of high-quality fruit.

Summary

Light utilization is the basis for the production of fruit. High light interception is needed for high yields and sufficient light exposure for flower-bud formation, fruit set, and characteristics of fruit quality. Light utilization is manipulated by planting density, arrangement, tree size and shape. The present study aimed at a quantification of light utilization in relation to apple production and external fruit quality as a function of geometrical properties of the orchard system.

Fruit growing has changed considerably during recent decades (Chapter 2). Higher planting densities have led to an important increase of production per ha. The Netherlands occupy a leading position in intensive fruit growing. The introduction of dwarfing rootstocks provided the basis for growth control at low planting densities. Dwarfing rootstocks come into earlier bearing. Currently, the unproductive phase has been reduced to just a few years. Furthermore, the production efficiency per tree is higher because more assimilates are allocated to fruit than is the case with vigorous rootstocks. Improved crop management, providing better control of diseases and pests and irrigation or fertigation to deal with competition for water and nutrients, has led to higher productivity as well.

Higher planting densities require an adapted planting system. Chapter 2 describes the development from large standard trees at 10 x 10 m spacings to the current densities of between 2000 and 4000 trees per ha. The single row is the most common planting system, but the associated relatively large area given to alleyways is a disadvantage in further intensification of planting density. Because the free-alley width must be at least 1.5 m for tractor access, planting distance within the row will become very small and the tree extremely compact, which may lead to insufficient light interception. For a given tree size, the relative area given to alleyways is smaller and more trees per ha can be arranged in multi-row systems. However, many multi-row systems have been found to perform similarly as or even worse than single rows. In particular, production and fruit quality of trees in the centre of the system are reduced. Light use efficiency is discussed in relation to trellised V- systems or horizontal, single- or multi-layered canopies versus vertical trees. Finally, the importance of row direction and the (small) effects of reflective materials in orchards are shown in Chapter 2.

A general simulation model on light absorption and crop photosynthesis was used to approach potential apple production for a range of latitudes in the temperate zone (35 to 55°) (Chapter 3). Here it was assumed that the growing season started earlier at a lower latitude. Daily photosynthesis was calculated with the use of a 3-point Gaussian integration over the day and over canopy depth. The canopy structure was assumed to be homogeneous. It was found that early cultivars, already ripening after four months, achieve about the same production at all latitudes. The lower light intensity at higher latitudes is compensated for by greater daylength and a more even distribution of the growing season around the longest day. Late cultivars, needing a longer season, produce more than early cultivars do and produce 1 to 2 tonnes per ha more per degree lower latitude. Because of a strong reduction in radiation at the end of the season, cultivars needing more than five to six months to ripen are unsuitable to grow at latitudes beyond 50°. Increased cloudiness is responsible for up to 18% less production at higher latitudes, compared to the results under brighter conditions at lower latitudes. A higher LAI, as can be expected in warmer regions or with vigorously growing cultivars, may lead to higher production up to LAI values of about 3.5. Higher LAI values promote production only slightly.

These calculations were based on the assumption of similar respiration costs for all latitudes. However, higher latitudes, being characterized by lower temperatures, may be associated with lower costs of maintenance respiration (Chapter 3). Respiration was estimated under the assumption of empirical relationships between temperature and respiration per organ. At an LAI value of 2, maintenance respiration was between 30 and 40% of gross photosynthesis, under the assumption that 16, 25, and 59% of dry matter is allocated to leaves, woody material (including roots), and fruit, respectively. Higher respiration costs at lower latitudes would lead to similar net photosynthesis between 35 and 45° in the period of four months after bloom. At higher latitudes, the level of net photosynthesis is lower. Later in the season, the proportion of respiration increases more at lower latitudes because of strongly reduced incoming radiation and hence of photosynthesis. Consequently, differences in production between latitudes become larger as the season progresses. In theory, maximum production will be achieved in regions with high light input and moderate temperature, which in fact is realized in New Zealand.

Not only gross photosynthesis, but respiration increases as well at a higher LAI. Leaves have high respiration costs. Therefore, high LAI values, which

contribute only slightly to more light absorption, can lead to marked reduction in net photosynthesis.

To quantify the influence of planting system and tree shape, we applied a simulation model that describes light transfer through trees (Chapters 4 and 5). The tree shape is approximated as cone, parabola, cylinder, or intermediate between cone and cylinder. Any number of similarly shaped trees can be positioned in any arrangement desired. The model distinguishes between direct and diffuse light. The agreement between calculated and measured light interception was generally good for various apple and pear orchards. Deviations were less than 10%. The model is extremely sensitive to tree dimension and leaf density.

For slender-spindle trees with a diameter of 1.25 m, calculation showed that the optimal density will be approximately 3000 trees per ha; more trees will only lead to more shaded crown volume due to overlap (Chapter 4). Multi-row systems intercept more light than would single rows at a given density. A greater proportion of shaded canopy is associated with multi-row systems on a triangular design than with single rows or multi-row systems with walking paths (Chapter 5). Light interception and the amount of well- illuminated crown volume will only increase with planting density under the constraints of reduced tree size and no increase in rectangularity or leaf density. Square planting is considered to be the optimal spacing with highest light interception and most uniform light distribution.

In experiments, planting density was found to be more important for yield than planting system (Chapter 6). Three-row bed systems on a triangular design (a system developed in North-Holland) were, however, less productive than other systems at a given density. A smaller tree did not give improved productivity. Production per ha of the North-Holland spindle, which is about 0.5 m smaller in diameter, was the same as or even lower than the slender spindle. However, the slender spindle produced less regularly than the North-Holland spindle. Additional summer pruning had no effect on yield. With the slender spindle, summer pruning was found to lead to fewer flowers and slightly more regular bearing, whereas the opposite was observed for the North-Holland spindle.

The influence of density, rectangularity, and tree height on production and fruit quality is discussed in Chapter 7. The experiment was carried out in The Netherlands and Denmark. Light interception and production per ha increased with planting density, but the number of well-coloured fruits did not

increase in later years, when light interception was between 70 and 90%. Reduction of tree height did not improve light penetration. On the contrary, the highest production of well-coloured fruits occurred in the tallest trees, even at the highest densities, which was due to a more open tree habit. Because plantings with ratio of between-to-within row distance of 1:1 and 2:1 intercepted light more efficiently than those at 3:1 designs did, the production of well-coloured fruit was higher. Fruit size was not affected by density, rectangularity, or tree height, probably due to sufficient leaf area per fruit. In The Netherlands, total fruit production and incoming radiation between bloom and harvest were 17 and 15% higher than in Denmark, respectively. These results were in agreement with production estimated with a crop-growth model. Fruits were smaller and less coloured at the higher latitude due to less light, lower temperatures, and heavier crop load.

The practical applications of the findings made in this study are discussed in Chapter 8. It is concluded that the optimal orchard system will be found in high planting density, low rectangularity and low leaf density. Planting density can be considerably lower in multi-row beds with walking paths, allowing the penetration of sufficient light into the trees, than in single rows. There are, however, agronomic reasons to prefer single rows, for example reduction of the herbicide-treated soil area, use of tunnel sprayers and mechanization. Single rows are associated with suboptimal light use. Intensification of a single row will only lead to higher production when a smaller within-row distance is accompanied by a smaller path width. Increasing tree height may improve light interception, too. It was predicted that, to obtain the same light interception, trees in single rows should be at least 0.5 m taller than those in multi-row systems.

Orchard productivity, mechanization possibilities, and the relative area occupied by alleyways are determined by the choice of planting density, planting system, and tree shape for many years. Optimization of the geometrical properties of the orchard system has therefore high strategic importance. Light interception can be considered an objective parameter for the evaluation of planting systems. The analytical approach has improved the understanding of the production potential in various orchard systems. For example, the crop-growth model shows the importance of climatic factors (light, temperature) for potential fruit production. Modelling of light interception is useful to optimize planting density, planting system, and tree dimensions, and may set priorities for future experiments. Modelling is also useful to improve the efficiency of studies particularly on perennial systems, where experiments are time and area-consuming.

Samenvatting

De benutting van zonlicht vormt de basis voor produktie en kwaliteit van fruit. Een hoge lichtopvang is belangrijk voor hoge produktie. Tevens is voldoende licht noodzakelijk voor bloemknopvorming, vruchtzetting, vruchtgroei, kleuring en smaak. Plantdichtheid, plantsysteem en boomvorm zijn factoren waarmee de lichtbenutting van een boomgaard kan worden gemanipuleerd. Het huidige onderzoek heeft zich gericht op een kwantificering van de invloed van licht op de produktie en uitwendige kwaliteit van appel in relatie tot geometrische eigenschappen van de beplanting.

In de laatste decennia zijn aanzienlijke veranderingen in de fruitteelt doorgevoerd (hoofdstuk 2). De toepassing van hogere plantdichtheden heeft geleid tot een belangrijke produktiestijging. Nederland neemt een vooraanstaande positie in bij deze intensivering. Het dichter planten is in de eerste plaats mogelijk gemaakt door de introductie van zwakke onderstammen, waarmee de produktie-efficiëntie wordt verhoogd. Bovendien wordt de groei per boom beter beheerst, wat heeft geleid tot een verkorting van de onproduktieve periode tot slechts enkele jaren. Ook in de beheersing van ziekten en plagen is grote vooruitgang geboekt, terwijl druppelbevloeiing en fertigatie zorgen voor een verbetering in de water- en nutriëntenvoorziening.

Een hogere plantdichtheid maakt aanpassingen in het plantsysteem noodzakelijk. In hoofdstuk 2 wordt de ontwikkeling van hoogstamboomgaarden met 100 bomen per ha naar de huidige rijensystemen met 2000 tot 4000 bomen per ha aan de hand van literatuur beschreven. De enkele rij is het meest voorkomende plantsysteem. Aan intensivering van een enkele rij zijn echter nadelen verbonden. Doordat een vrije padbreedte van zeker 1,5 m vereist is voor machines, wordt de plantafstand bij hoge dichtheden op de rij bijzonder klein. Dat kan leiden tot onvoldoende lichtbenutting. Bij meerrijsystemen is de onbenutte ruimte minder groot en kunnen meer bomen per ha gerangschikt worden voor een gegeven boomgrootte. In de praktijk voldoen veel meerrijsystemen echter niet of nauwelijks beter dan enkele rijen. Produktie en vruchtkwaliteit van de zogenaamde binnenbomen blijven vaak achter, wat grote gevolgen heeft voor de economische produktie. De lichtbenutting van systemen met schuin opgekweekte bomen, zoals V-hagen, of met (horizontale) tafelsystemen, wordt vergeleken met die van rechtopstaande bomen. Hoofdstuk 2 schetst tenslotte het belang van rijrichting en de (geringe) effecten van reflecterend materiaal in de boomgaard op lichtintensiteit, produktie en kwaliteit.

Met behulp van een algemeen fysiologisch model is in hoofdstuk 3 de relatie tussen lichtabsorptie en potentiële appelproduktie onderzocht in de gematigde zone (breedtegraad 35 tot 55°). Er werd rekening gehouden met een later begin van het seizoen bij een hogere breedtegraad. De fotosynthese werd berekend met behulp van een integratie volgens Gauss over drie momenten per dag en drie diepten in de beplanting. Het gewas werd verondersteld homogeen te zijn.

Volgens dit model bereiken vroege rassen met een groeiseizoen van ongeveer vier maanden eenzelfde produktie op uiteenlopende breedtegraden. De lagere lichtintensiteit op hogere breedtegraden wordt gecompenseerd door langere dagen en een gunstiger spreiding van het seizoen rond de langste dag. Late rassen met een langer seizoen kunnen meer produceren dan vroege rassen en bereiken bovendien een hoger produktieniveau op een lagere breedtegraad. De voorspelde verschillen bedragen 1 tot 2 ton per ha per breedtegraad. Vanwege een sterke vermindering van instraling in de herfst lijken rassen met een groeiseizoen langer dan vijf of zes maanden niet meer interessant voor breedtegraden boven 50.

De sterkere bewolkingsgraad op hogere breedtegraden leidt tot een vermindering van de potentiële produktie van maximaal 18 %, vergeleken met de zonniger omstandigheden op lagere breedtes. In warmere gebieden of bij bepaalde groeikrachtige rassen wordt meer blad ontwikkeld. Dit leidt bij LAI-waarden tot 3,5 tot een belangrijke produktiestijging, maar heeft bij hogere waarden slechts weinig effect.

Het is aannemelijk dat bij hogere breedtegraden dankzij de gewoonlijk lagere temperaturen de onderhoudsademhaling geringer is. De verschillen in ademhaling tussen breedtegraden zijn modelmatig benaderd (hoofdstuk 3). Hiertoe zijn gemiddelde dagtemperaturen gebruikt en experimentele relaties tussen temperatuur en ademhaling van verschillende organen. Bij een LAI van 2 en een empirische verdeling van droge stof over bladeren (16 %), houtige delen inclusief wortels (25 %) en vruchten (59 %), blijkt de onderhoudsademhaling verantwoordelijk te zijn voor 30 tot 40 % van de bruto fotosynthese. Vier maanden na de bloei is de netto fotosynthese ongeveer gelijk tussen 35 en 45° breedte, maar kleiner bij hogere breedtegraden. Naarmate het seizoen vordert, worden de potentiële verschillen in produktie tussen breedtegraden nog groter vanwege een sterke afname in instraling op de hogere breedtegraden. De hoogste produktie wordt in theorie bereikt in een klimaat met veel licht en gematigde temperaturen. In Nieuw-Zeeland wordt aan deze voorwaarden voldaan en worden inderdaad topprodukties gerealiseerd.

Bij een hogere LAI neemt niet alleen de bruto fotosynthese, maar ook de ademhaling toe. Bladeren zijn echter duur in onderhoud. Een LAI boven 3.5, die slechts weinig bijdraagt aan meer lichtabsorptie, kan daardoor leiden tot een aanzienlijke netto daling in produktie.

Om de invloed van plantsysteem en boomvorm te kwantificeren, is een simulatiemodel toegepast, dat in drie dimensies lichtuitdoving in bomen beschrijft (hoofdstuk 4 en 5). De boom wordt benaderd in de vorm van een kegel, parabool, cylinder of een tussenvorm van kegel en cylinder. Elke willekeurige plantdichtheid, rangschikking en boomgrootte kan worden ingevoerd. Onderscheid wordt gemaakt tussen direct en diffuus licht. Uitkomsten van dit model zijn getoetst aan waarnemingen in diverse appel- en perebeplantingen. De algemene overeenkomst tussen model en metingen was goed; afwijkingen waren doorgaans kleiner dan 10 %. Het model is vooral gevoelig voor boomomvang en bladerdichtheid.

Voor slanke spillen met een diameter van 1,25 m is berekend dat de optimale plantdichtheid ongeveer 3000 bomen per ha zou bedragen. Met meer bomen per ha neemt de beschaduwing sterk toe doordat de bomen elkaar te veel overlappen (hoofdstuk 4). Meerrijsystemen vangen in theorie meer licht op dan enkele rijen, zelfs bij dezelfde plantdichtheid. De lichttoetreding in drierijige bedden in driehoeksverband is echter minder gunstig dan in andere systemen. Bedden met looppaadjes functioneren beter in dit opzicht (hoofdstuk 5). Met kleinere bomen en hogere plantdichtheden kan meer licht worden opgevangen en neemt de beschaduwing in de boom niet toe tenzij de hogere plantdichtheid gepaard gaat met een te grote boom, een hogere bladerdichtheid of een meer "rechthoekig" plantverband. Een vierkantsverband heeft in theorie de hoogste lichtopvang en beste lichtverdeling.

In hoofdstuk 6 blijkt dat het plantsysteem in de praktijk van geringer belang is dan de plantdichtheid. Drierijige bedden in driehoeksverband (een in Noord-Holland ontwikkeld systeem) waren echter in verhouding tot andere systemen minder produktief. Dit resultaat wordt ondersteund door de theoretische berekeningen over lichtdoordringing in het centrum van deze bedden. In de praktijk probeert men de produktiviteit te verbeteren door een slankere boom toe te passen. In hierop gerichte proeven is dit echter niet gelukt. De produktie per ha van de Noordhollandse spil, die ongeveer 50 cm smaller is dan de slanke spil, was gelijk aan of zelfs lager dan die van de slanke spil.

Wel produceerde de slanke spil minder regelmatig dan de Noordhollandse spil. Uit de proef bleek tenslotte dat een lichte zomersnoei geen invloed had op het produktieniveau, maar wel een bescheiden rol speelde in produktieregelmaat. Zomersnoei leidde tot minder bloemknoppen en regelmatiger produktie bij de slanke spil. Bij de Noordhollandse spil was dit juist andersom.

Hoofdstuk 7 behandelt een proef waarin de invloed van plantdichtheid op lichtopvang, produktie en vruchtkwaliteit wordt beschreven in combinatie met rangschikking en boomhoogte. De proef werd uitgevoerd in Nederland en Denemarken. Lichtopvang en produktie per ha namen toe met de plantdichtheid. In de volgroeide fase nam de produktie van goed gekleurd fruit echter niet meer toe. Dit werd verklaard uit een zeer hoge lichtopvang (70 tot 90 %), leidend tot onvoldoende lichtdoordringing in een groot deel van de boom. Een lagere boom verbeterde de lichtdoordringing niet. Integendeel, dankzij een lagere bladerdichtheid produceerden juist de hoogste bomen het meeste goed gekleurde fruit, zelfs bij de hogere dichtheden. De verhouding van afstand van bomen tussen en op de rij had een grote invloed op de produktie. Bij plantverbanden met een verhouding van 1:1 of 2:1 werd meer licht opgevangen en werd dit licht bovendien regelmatiger verdeeld dan bij 3:1 systemen. Dit leidde tot een hogere produktie en meer goed gekleurde vruchten. De vruchtgrootte had in deze proef geen relatie met boomgaardfactoren. Waarschijnlijk was dit het gevolg van een hoge blad-vruchtverhouding in alle behandelingen.

De totale produktie in Nederland was 17 % hoger dan in Denemarken. Inkomende straling gedurende het groeiseizoen was gemiddeld 15 % hoger. Deze resultaten kwamen overeen met schattingen van de potentiële produktie op grond van lichtabsorptie, zoals berekend met het gewasgroeimodel. De vruchten waren bovendien kleiner en minder goed gekleurd op de hogere breedtegraad, als gevolg van minder licht, een lagere temperatuur en een zwaardere vruchtdracht.

Hoofdstuk 8 gaat in op mogelijke toepassingen van dit onderzoek voor de praktijk. Een belangrijke conclusie is dat het optimale plantsysteem gevonden dient te worden in een combinatie van een hoge plantdichtheid met een lage verhouding van padbreedte en afstand op de rij en een lage bladerdichtheid. Met beddensystemen met looppaden zijn aanmerkelijk minder bomen per ha nodig om tot een bepaalde produktie te komen dan met enkele rijen. In de praktijk gaat de voorkeur momenteel echter uit naar enkele rijen. Hieraan liggen andere overwegingen ten grondslag, zoals de versmalling van de zwartstrook in verband met herbicidengebruik, overkapt spuiten en mechanisatie van bodembewerking. Enkele rijen hebben geen optimale lichtbenutting. Intensivering van een enkele rij zal alleen leiden tot een verhoging van de produktie, wanneer een kleinere afstand op de rij gepaard gaat met een versmalling van het pad. Ook een hogere boom kan de lichtopvang vergroten. Om eenzelfde lichtopvang als een meerrijsysteem te bereiken, dient de boom in een enkele rij zeker 0,5 m hoger te zijn dan in een meerrijig bed.

Met plantdichtheid, plantsysteem en boomvorm worden potentiële produktie en kwaliteit van een beplanting voor jaren vastgelegd. Ook andere aspecten van de teelt, zoals de mogelijkheden tot mechanisatie en de verhouding van oppervlak van rijpaden tot beplant oppervlak, worden met de keuze van het plantsysteem bepaald. Optimalisering van de geometrische eigenschappen van een beplanting is daarom van groot strategisch belang. Lichtopvang kan beschouwd worden als een objectieve maat in het beoordelen van plantsystemen en is bovendien eenvoudig te meten. De waarde van modellen ligt vooral in het analyseren van de invloed van klimaats- en boomgaardfactoren. Klimatologische randvoorwaarden voor de potentiële produktie van fruit (licht, temperatuur) zijn te kwantificeren. Het lichtverdelingsmodel kan een bruikbaar instrument zijn bij het optimaliseren van plantdichtheid, plantsysteem en dimensies van de boom. Daarnaast kan dit model van nut zijn bij het ontwerpen van proeven en de omvang van proefvelden. Vooral bij overblijvende gewassen, waar experimenten tijdrovend zijn en veel ruimte vergen, kan toepassing van modellen de onderzoeksefficiëntie belangrijk verhogen.

References

Abbott, D.L., 1984. The apple tree: physiology and management. Grower Books, London, 63 pp.

Aikman, D.P., 1989. Potential increase in photosynthetic efficiency from the redistribution of solar radiation in a crop. J. Exp. Bot., 40: 855–865.

Amthor, J.S., 1989. Respiration and crop productivity. Springer Verlag, New York, 215 pp.

Anonymus, 1994. Gewasbescherming en groeiregulatie in de fruitteelt. Nederlandse Fruittelers Organisatie, Den Haag, 67 pp.

Archbold, D.D., Brown, G.R. and Cornelius, P.L., 1987. Rootstock and in-row spacing effects on growth and yield of spur-type 'Delicious' and 'Golden Delicious' apple. J. Amer. Soc. Hortic. Sci., 112: 219–222.

Arthey, V.D., 1975. Quality of horticultural products. Butterworths, London, 228 pp.

Atkinson, D., 1981. Water use and the control of water stress in high density plantings. Acta Hortic., 114: 45–56.

Atkinson, D., Naylor, D. and Coldrick, G.A., 1976. The effect of tree spacing on the apple root system. Hortic. Res., 16: 89–105.

Auchter, E.C., Schrader, A.L., Lagasse, F.S. and Aldrich, W.W., 1926. The effect of shade on the growth, fruit bud formation and chemical composition of apple trees. Proc. Amer. Soc. Hortic. Sci., 23: 368–382.

Avery, D.J., 1969. Comparisons of fruiting and deblossomed maiden apple trees, and of non-fruiting trees on a dwarfing and an invigorating rootstock. New Phytol., 68: 323–336.

Avery, D.J., 1970. Effects of fruiting on the growth of apple trees on four rootstock varieties. New Phytol., 69: 19–30.

Avery, D.J., 1977. Maximum photosynthetic rate – a case study in apple. New Phytol., 78: 55–63.

Avery, D.J., Priestley, C.A. and Treharne, K.J., 1979. Integration of assimilation and carbohydrate utilization in apple. In: K. Marcelle, H. Clijsters and H. van Poucke (Editors), Photosynthesis and plant development. Dr W. Junk, The Hague, pp. 221–231.

Baldini, E. and Rossi, F., 1987. Radiant energy spectral distribution in fruit tree canopy. In: F. Prodi, F. Rossi and G. Cristoferi (Editors), Int. Conf. Agrometeorol., Cesena 1987, Fondazione Cesena Agricultura Publ., Italy, pp. 401–408.

Barritt, B.H., 1989. Influence of orchard system on development, light interception and production of third-year Granny Smith apple trees. Acta Hortic., 243: 121–130.

Barritt, B.H., 1991. The 'hybrid tree cone' training for apple orchards. Good Fruit Grower, 42(3): 12–16.

Barritt, B.H. and Rom, C.R., 1987. Renovating mature apple trees- fruit quality through stronger spurs and better light distribution. Compact Fruit Tree, 20: 70–75.

Barritt, B.H., Rom, C.R., Konishi, B.J. and Dilley, M.A., 1991. Light level influences spur quality and canopy development and light interception influence fruit production in apple. HortSci., 26: 993–999.

Berry, G., 1967. A mathematical model relating plant yield with arrangement for regularly spaced crops. Biometrics, 23: 505–515.

Black, J.N., 1956. The distribution of solar radiation over the earth's surface. Arch. Meteorol. Geophys. Bioklimatol. B. Bd. 7, H.2: 165–189.

Blanke, M., 1988. Wieviel Kohlenstoff veratmet eine Apfelfrucht während ihrer Entwicklung? Erwerbsobstbau, 30: 68–70.

Blanke, M. and Lenz, F., 1988. Kann die Apfelfrucht selbst zur Stoffbildung beitragen? Erwerbsobstbau, 30: 44–47.

Buban, T. and Faust, M., 1982. Flower bud induction in apple trees: internal control and differentiation. Hortic. Rev., 4: 174–203.

Butler, D.R. and Landsberg, J.J., 1981. Respiration rates of apple trees, estimated by CO_2-efflux measurements. Plant, Cell and Environ., 4: 153–159.

Buwalda, J.G., 1991. A mathematical model of carbon acquisition and utilisation by kiwifruit vines. Ecol. Modelling, 57: 43–64.

Buwalda, J.G., Fossen, M. and Lenz, F., 1992. Carbon dioxide efflux from roots of calamodin and apple. Tree Physiol., 10: 391–401.

Byers, R.E., Carbaugh, D.H., Presley, C.N. and Wolf, T.K., 1991. The influence of low light on apple fruit abscission. J. Hortic. Sci., 66: 7–17.

Cahn, M.B. and Goedegebure, J., 1991. Economical analysis of Elstar planting systems trial. Ann. Rep. 1990, Res. Sta. Fruit Growing, Wilhelminadorp, pp. 57–61.

Cahn-Shaharudin, M. and Goedegebure, K., 1991. Intensiveren tot 4000 bomen geeft betere resultaten. De Fruitteelt, 81(1): 12–14.

Cain, J.C., 1971. Effects of mechanical pruning of apple hedgerows with a slotting saw on light penetration and fruiting. J. Amer. Soc. Hortic. Sci., 96: 664–667.

Cain, J.C., 1972. Hedgerow orchard design for most efficient interception of solar radiation. Effects of tree size, shape, spacing, and row direction. NY St. Agric. Exp. Sta., Search Agric., 2(7): 1–14.

Cain, J.C., 1973. Foliage canopy development of 'McIntosh' apple hedgerows in relation to mechanical pruning, the interception of solar radiation, and fruiting. J. Amer. Soc. Hortic. Sci., 98: 357–360.

Callesen, O., 1988. Effect of flower bud position on fruit set and fruit size in apple. Danisch J. Plant Soil Sci., 92: 339–344.

Callesen, O., 1993. Influence of apple tree height on yield and fruit quality. Acta Hortic., 349: 111–115.

Callesen, O. and Wagenmakers, P.S., 1989. Effect of tree density, tree height and rectangularity on growth, flowering, and fruit production. Acta Hortic., 243: 141–148.

Casal, J.J. and Smith, H., 1989. The functioning, action and adaptive significance of phytochrome in light-grown plants. Plant, Cell and Environ., 12: 855–862.

Cervenka, K., 1978. Orientierung der Blätter in den Apfelkronen und Absorption der Sonnenstrahlung. Arch. Gartenbau, 26: 373–385.

Chalmers, D.J., Vandenende, B. and VanHeek, L., 1978. Productivity and mechanisation of the Tatura trellis orchard. HortSci., 13: 517–521.

Charles-Edwards, D.A., 1982. Physiological determinants of crop growth. Academic Press, Sydney New York London, 161 pp.

Charles-Edwards, D.A. and Thorpe, M.R., 1976. Interception of diffuse and direct-beam radiation by a hedgerow apple orchard. Ann. Bot., 40: 603–613.

Clayton-Greene, K.A., 1989. Apple production and tree training. Compact Fruit Tree, 22: 8–11.

Clayton-Greene, K.A., Reynolds, J. and Ferree, D.C., 1993. Influence of orchard management system on leaf angle and leaf orientation in apple trees. J. Hortic. Sci., 68: 679–687.

Cooper, J.P., 1975. Control of photosynthetic production in terrestrial systems. In: J.P. Cooper (Editor), Photosynthesis and productivity in different environments, Cambridge Univ. Press, Cambridge, pp. 593–621.

Cordes, D., 1988. Atmung und Transpiration von Apfeltrieben in Abhängigkeit von Entblätterung und veränderten Klimafaktoren. Gartenbauwiss., 53: 151–155.

Corelli, L. and Sansavini, S., 1989. Light interception and photosynthesis related to planting density and canopy management in apple. Acta Hortic., 243: 159–174.

Cripps, J.E.L., Melville, F. and Nichol, H.I., 1975. The relationship of 'Granny Smith' apple tree growth and early cropping to plant density and rectangularity. J. Hortic. Sci., 50: 291–299.

Davis, L.D., 1957. Flowering and alternate bearing. Proc. Amer. Soc. Hortic. Sci., 70: 545–556.

DeJong, T.M. and Day, K.R. (1991). Relationships between shoot productivity and leaf characteristics in peach canopies. HortSci., 26: 1271–1273.

Denholm, J.V. and Connor, D.J., 1982. Photosynthetic potential in trellis-type orchard canopies. Austr. J. Plant Physiol., 9: 629–640.

Devyatov, A.S. and Gorney, A.V., 1978. Effect of espalier orientation on light status and cropping of apple trees. Fruit Sci. Rep., V(4): 1–8.

Dunn, J.S. and Stolp, M., 1981. Apple production for mechanised harvesting on the Lincoln canopy system. NZ Agric. Eng. Inst., Ext. Bull., no. 10.

Ebert, G., 1991. Die Wurzelatmung von Apfelbäumen. I. Einfluss von Umweltfaktoren. Erwerbsobstbau, 33: 227–230.

Elfving, D.C., Schechter, I., Cline, R.A. and Pierce, W.F., 1990. Palmette-leader and central-leader tree forms compared for light distribution, productivity, and fruit quality of 'McIntosh' apple trees. HortSci., 25: 1386–1388.

Engel, G., 1987. Praxisorientierte Pflanzsysteme im Apfelanbau. Mitt. Obstbauversuchsringes des Alten Landes, 42: 253–261.

Erez, A., 1978. Adaptation of the peach to the meadow orchard system. Acta Hortic., 65: 245–250.

Evans, L.T., 1990. Assimilation, allocation, explanation, extrapolation. In: Rabbinge, R., Goudriaan, J., Keulen, H. van, Penning de Vries, F.W.T. and Laar, H.H. van (Editors). Theoretial production ecology: reflections and prospects. Pudoc, Wageningen, pp. 77–87.

Evéquoz, M., 1988. La conduite en fuseau double, nouvelle forme pour l'arboriculteur. Rev. Suisse Vit. Arbor. Hortic., 20: 369–371.

Ferree, D.C., 1989. Influence of orchard management systems on spur quality, light, and fruit within the canopy of 'Golden Delicious' apple trees. J. Amer. Soc. Hortic. Sci., 114: 869–875.

Ferree, D.C. and Carlson, R.F., 1987. Apple rootstocks, In: R.C. Rom and R.F. Carlson (Editors), Rootstocks for fruit crops, John Wiley and Sons, New York, pp. 107–143.

Ferree, D.C., Schupp, J.R., Blizzard, S.H., Baugher, T.A. and Warrington, I.J., 1989. Influence of five orchard management systems on canopy position, light penetration, and net photosynthesis of 'Golden Delicious' apple. Acta Hortic., 243: 131–140.

Flierman, J., 1977. Attentie voor de Noordhollandse snoei. De Fruitteelt, 67: 968–971.

Forshey, C.G., 1990. Factors affecting 'Empire' fruit size. NY St. Hortic. Soc., Proc. Ann. Meeting, Vol. 135, pp. 71–74.

Forshey, C.G. and McKee, M.W., 1970. Production efficiency of a large and a small 'McIntosh' apple tree. HortSci., 5: 164–165.

Forshey, C.G., Weires, R.W. and Vankirk, J.R., 1987. Seasonal development of the leaf canopy of 'Macspur McIntosh' apple trees. HortSci., 22: 881–883.

Free, J.B., 1962. The effect of distance from pollinizer varieties on the fruit set on trees in plum and apple orchards. J. Hortic. Sci., 37: 262–271.

Fukuda, H., Kudo, K., Kashimura, Y., Nishiyama, Y., Takishita, F., Kubota, T. and Chiba, K., 1987. Growth of apple trees on dwarf rootstocks in high density orchards. I. Production of apple trees on dwarf rootstocks. Bull. Fruit Tree Res. Sta., Morioka, 14: 27–38.

Gardner, V.R., Bradford, F.C. and Hooker, H.D. Jr., 1922. The fundamentals of fruit production, McGraw-Hill Book Company, New York, 686 pp.

Geisler, D. and Ferree, D.C., 1984. Response of plants to root pruning. Hortic. Rev., 6: 155–181.

Gendt, C.M.E. de, 1992. Dry-matter partitioning of Summerred. Ann. Rep. 1991, Res. Sta. Fruit Growing, Wilhelminadorp, pp. 34–37.

Gendt, C.M.E. de, 1993. Dry matter partitioning in the tree. Ann. Rep. 1992, Res. Sta. Fruit Growing, Wilhelminadorp, pp. 33–34.

Goedegebure, J., 1976. Bedrijfseconomische aspecten van intensieve appelbeplantingen. Landbouw-Economisch Instituut, Den Haag, No. 4.70, 44 pp.

Goedegebure, J., 1978. Business-economic aspects of high density plantings in the Netherlands. Acta Hortic., 65: 21–29.

Goedegebure, J., 1984. Economische aspecten van de plantdichtheid bij appel. De Fruitteelt, 69: 164–167.

Goedegebure, J., 1986. A calculation model for investments in perennial plantings. Acta Hortic., 184: 183–189.

Goedegebure, J., 1987. Toekomstige ontwikkelingen in de fruitteelt. De Fruitteelt, 7: 10–12.

Goedegebure, J., 1993. Economic aspects of super-intensive apple orchards. Acta Hortic., 349: 285–293.

Goedegebure, J., Groot, M., Diepen, S. van, Hilberts, W. and Bus, H., 1994. De concurrentiepositie van Nederlandse peren in Europa. Nederlandse Fruittelers Organisatie, Den Haag, 26 pp.

Goedegebure, J., Joosse, M.L. and Merkens, J., 1991. Internationale concurrentiepositie van de Nederlandse appelteelt; bedrijfseconomische en marktkundige evaluatie. Landbouweconomisch Instituut, Onderzoeksverslag 75, Den Haag, 91 pp.

Goudriaan, J., 1977. Crop micrometeorology: a simulation study. Pudoc, Wageningen, 249 pp.

Goudriaan, J., 1988. The bare bones of leaf-angle distribution in radiation models for canopy photosynthesis and energy exchange. Agric. For. Meteorol., 43: 155–169.

Goudriaan, J., Laar, H.H. van, Keulen, H. van and Louwerse, W., 1985. Photosynthesis, CO_2 and plant production. In: W. Day and R.K. Atkin (Editors), Wheat growth and modeling. NATO ASI Series. Series A: Life Sciences Vol. 86, pp. 107–122.

Grace, J.C., 1988. Effect of tree arrangement on intercepted radiant energy and photosynthesis. In: A.R. Ek, S.R. Shifley and T.E. Burk (Editors), Forest Growth Modelling and Prediction, Vol. 1, Proc. IUFRO Conf., Gen. Techn. Rep. USDA North Central For. Expt. Sta., NC 120: 285–292.

Grantz, D.A., Zhang, X.J., Metheney, P.D. and Grimes, D.W., 1994. Indirect measurement of leaf area index in Pima cotton (Gossypium barbadense L.) using a commercial gap inversion method. Agric. For. Meteorol., 67: 1–12.

Hall, A.D. and Crane, M.B., 1933. The apple. Martin Hopkinson Ltd., London, pp. 17–26.

Hansen, P., 1967. 14C-studies on apple trees. I. The effect of the fruit on the translocation and distribution of photosynthates. Physiol. Plant., 20: 382–391.

Hansen, P. and Grauslund, J., 1980. Blomsterknopdannelse hos æbletræer. Nogle virkninger af bæring, vækst og klima. Statens Planteavlsforsøg, 1504: 215–227.

Hansen, P. and Stoyanov, S., 1972. Frugtudtynding II. Den nødvendige bladmængde til forsyning af frugten hos forskellige æblesorter. Tidsskrift Planteavl, 76: 646–652.

Heim, G., Landsberg, J.J., Watson, R.L. and Brain, P., 1979. Eco-physiology of apple trees: dry matter production and partitioning by young Golden Delicious trees in France and England. J. Appl. Ecol., 16: 179–194.

Heinicke, D.R., 1964. The microclimate of fruit trees. III. The effect of tree size on light penetration and leaf area in Red Delicious apple trees. Proc. Amer. Soc. Hortic. Sci., 85: 33–41.

Huang, S.B., 1990. Agroclimatology of the major fruit production in China: a review of current practice. Agric. For. Meteorol., 53: 125–142.

Hugard, J., 1981. High density plantings in French orchards: developments and current achievements. Acta Hortic., 114: 300–308.

Hunter, D.M. and Proctor, J.T.A., 1986. The correlation of light interception with yield and fruit colour of McIntosh apple strains. Fruit Var. J., 40(3): 79–83.

Jackson, J.E., 1970. Aspects of light climate within apple orchards. J. Appl. Ecol., 7: 207–216.

Jackson, J.E., 1978. Utilization of light resources by HDP systems. Acta Hortic., 65: 61–70.

Jackson, J.E., 1980. Light interception and utilization by orchard systems. Hortic. Rev., 2: 208–267.

Jackson, J.E., 1985. Future fruit orchard design: economics and biology. In: M.G.R. Cannell and J.E. Jackson (Editors), Trees as crop plants. Inst. Terr. Ecol., Huntingdon, UK, pp. 441–459.

Jackson, J.E., 1989a. Tree and crop selection and management to optimize overall system productivity, especially light utilization, in agroforestry. In: W.S. Reifsnyder and T.O. Darnhofer (Editors), Meteorology and agroforestry. Proceedings of an international workshop on the application of meteorology to agroforestry systems planning and management, Nairobi 1987, pp. 163–173.

Jackson, J.E., 1989b. World-wide development of high density planting in research and practice. Acta Hortic., 243: 17–27.

Jackson, J.E. and Palmer, J.W., 1972. Interception of light by model hedgerow orchards in relation to latitude, time of year and hedgerow configuration and orientation. J. Appl. Ecol., 9: 341–357.

Jackson, J.E. and Palmer, J.W., 1973. Effects of tree population and variations in spacing within and between rows of Golden Delicious on M.9. East Malling Res. Sta., Ann. Rep. 1972, pp. 54–55.

Jackson J.E. and Palmer, J.W., 1977. Effects of shade on the growth and cropping of apple trees. I. Experimental details and effects on vegetative growth. J. Hortic. Sci., 52: 245–252.

Jackson, J.E. and Palmer, J.W., 1979. A simple model of light transmission and interception by discontinuous canopies. Ann. Bot., 44: 381–383.

Jackson, J.E., Parry, M.S. and Stephens, C.P., 1981. Intensification of tree fruit production: current constraints, relevant research and an alternative system strategy for the 1980s. Acta Hortic., 114: 399–406.

Jackson, J.E., Sharples, R.O. and Palmer, J.W., 1971. The influence of shade and within-tree position on apple fruit size, colour and storage quality. J. Hortic. Sci., 46: 277–287.

Johnson, R.S. and Lakso, A.N., 1985. Relationships between stem length, leaf area, stem weight, and accumulated growing degree-days in apple shoots. J. Amer. Soc. Hortic. Sci., 110: 586–590.

Johnson, R.S. and Lakso, A.N., 1986. Carbon balance model of a growing apple shoot: I. Development of the model. J. Amer. Soc. Hortic. Sci., 111: 160–164.

Jones, H.G., 1983. Plants and microclimate, Cambridge Univ. Press, Cambridge, 323 pp.

Jones, H.G., Lakso, A.N. and Syvertsen, J.P., 1985. Physiological control of water status in temperate and subtropical fruit trees. Hortic. Rev., 7: 301–344.

Keppel, H., 1987. Erfahrungen mit der Erziehungsform 'Schlanke Spindel' in verschiedenen Pflanzensystemen und bei unterschiedlichen Standweiten unter Standortsbedingungen der Steiermark. III. Mitteilung: Beobachtungen und Untersuchungen bei der Apfelsorte Jonagold. Bodenkultur 38(3): 257–272.

Kira, T., 1975. Primary production of forests. In: J.P. Cooper (Editor), Photosynthesis and productivity in different environments. Cambridge Univ. Press, Cambridge, pp. 5–40.

Kodde, J. and Kipp, J.A., 1990. Meer zicht op waterverbruik appelbomen. Fruitteelt, 80(26): 13–14.

Kraalingen, D.W.G. van, Breure, C.J. and Spitters, C.J.T., 1989. Simulation of oil palm growth and yield. Agric. For. Meteorol., 46: 227–244.

Kriedemann, P.E. and Canterford, R.L., 1971. The photosynthetic activity of pear leaves (Pyrus communis L.). Austr. J. Biol. Sci., 24: 197–205.

Kronenberg, H.G., 1989. Apple growing potentials in Europe. 3. Northern limits. Neth. J. Agric. Sci., 37: 35–45.

Lakso, A.N., 1984. Leaf area development patterns in young pruned and unpruned apple trees. J. Amer. Soc. Hortic. Sci., 109: 861–866.

Lakso, A.N. and Corelli Grappadelli, L., 1992. Implications of pruning and training practices to carbon partitioning and fruit development in apple. Acta Hortic., 322: 231–239.

Lakso, A.N. and Goffinet, M.C., 1987. Aspects of fruit size development in apples. Compact Fruit Tree, 20: 104–106.

Lakso, A.N. and Johnson, R.S., 1990. A simplified dry matter production model for apple using automatic programming simulation software. Acta Hortic., 276: 141–148.

Lakso, A.N. and Musselman, R.C., 1976. Effects of cloudiness on interior diffuse light in apple trees. J. Amer. Soc. Hortic. Sci., 101: 642–644.

Lakso, A.N., Robinson, T.L. and Carpenter, S.G., 1989a. The palmette leader: a tree design for improved light distribution. HortSci., 24: 271–275.

Lakso, A.N., Robinson, T.L. and Pool, R.M., 1989b. Canopy microclimate effects on patterns of fruiting and fruit development in apples and grapes. In: C.J. Wright (Editor), Manipulation of Fruiting. Butterworths, London, pp. 263–274.

Landsberg, J.J., 1974. Apple fruit bud development and growth; analysis and an empirical model. Ann. Bot., 38: 1013–1023.

Landsberg, J.J., Powell, D.B.B. and Butler, D.B., 1973. Microclimate in an apple orchard. J. Appl. Ecol., 10: 881–896.

Landsberg, J.J. and Thorpe, M.R., 1975. The mechanisms of apple bud morphogenesis: analysis and a model. Ann. Bot., 39: 689–699.

Lanen, H.A.J. van, Hendriks, C.M.A. and Bulens, J.D., 1992. Crop production potential of rural areas within the European Communities. V: Qualitative suitability assessment for forestry and fruit crops. Netherlands Scientific Council for Government Policy, Working Documents, W69, 188 pp.

Lang, A.R.G. and Yueqin, X., 1986. Estimation of leaf area index from transmission of direct sunlight in discontinuous canopies. Agric. For. Meteorol., 37: 229–243.

Lespinasse, J.M. and Delort, J.F., 1986. Apple tree management in vertical axis: appraisal after ten years of experiments. Acta Hortic., 160: 139–155.

Lokeren Campagne, P. van and Werken, J. van de, 1984. Onderzoek van het plukbandensysteem voor de oogst van appels en peren in volveldsbeplantingen. IMAG Wageningen, rapp. 64, 56 pp.

Lombard, P.B. and Westwood, M.N., 1977. Effect of hedgerow orientation on pear fruiting. Acta Hortic., 69: 175–169.

Lord, W.J., Greene, D.W. and Damon, R.A. jr., 1979. Flowering of young apple trees following summer pruning. J. Amer. Soc. Hortic. Sci., 104: 540–544.

Luckwill, L.C., 1970. The control of growth and fruitfulness of apple trees. In: L.C. Luckwill and C.V. Cutting (Editors), Physiology of tree crops. Academic Press, London and New York, pp. 237–254.

Luckwill, L.C., 1978. Meadow orchards and fruit walls. Acta Hortic., 65: 237–243.

Maas, M.P. van der and Bolding, P.J., 1994. Sturing van groei en vruchtbaarheid van pit- en steenvruchten via de water- en nutriëntenvoorziening. Jaarverslag 1993, Proefstation voor de Fruitteelt, Wilhelminadorp, pp. 126–131.

Maggs, D.H., 1963. The reduction in growth of apple trees brought about by fruiting. J. Hortic. Sci., 38: 119–128.

Marini, R.P. and Barden, J.A., 1982a. Growth and flowering of vigorous apple trees as affected by summer or dormant pruning. J. Amer. Soc. Hortic. Sci., 107: 34–39.

Marini, R.P and Barden, J.A., 1982b. Light penetration on overcast and clear days, and specific leaf weight in apple trees as affected by summer or dormant pruning. J. Amer. Soc. Hortic. Sci., 107: 39–43.

Marini, R.P. and Barden, J.A., 1982c. Yield, fruit size, and quality of three apple cultivars as influenced by summer or dormant pruning. J. Amer. Soc. Hortic. Sci., 107: 474–479.

Mika, A., 1980. The influence of reflective mulch on illumination of the apple tree canopy and on fruit quality. Fruit Sci. Rep., VII(1): 15–23.

Mika, A., 1986. Physiological responses of fruit trees to pruning. Hortic. Rev., 8: 337–378.

Mika, A., Grochowska, M.J. and Karaszewska, A., 1977. Studies on the physiological aspects of pruning of apple trees. I. The effect of pruning and disbudding on fruit bud formation and dry matter increment of maiden apple trees. Fruit Sci. Rep., IV(3): 1–5.

Mitchell, P.D., Vandenende, B., Jerie, P.H. and Chalmers, D.J., 1989. Responses of 'Bartlett' pear to withholding irrigation, regulated deficit irrigation, and tree spacing. J. Amer. Soc. Hortic. Sci., 114: 15–19.

Mohren, G.M.J., 1987. Simulation of forest growth, applied to Douglas fir stands in The Netherlands. Thesis, Agric. Univ., Wageningen, 184 pp.

Mohren, G.M.J., Jorritsma, I.T.M., Florax, J.P.G.G.M. and Veen, J.R. van de, 1990. FORGRO 3.0: a basic forest growth model. Instituut voor Bosbouw en Groenbeheer "De Dorschkamp", Wageningen.

Monselise, S.P. and Goldschmidt, E.E., 1982. Alternate bearing in fruit trees. Hortic. Rev., 4: 128–173.

Monsi, M. and Saeki, T., 1953. Uber den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung für die Stoffproduktion. Jpn. J. Bot., 14: 22–52.

Monteith, J.L., 1977. Climate and the efficiency of crop production in Britain. Philos. Trans. R. Soc. London, B., 281: 277–294.

Monteith, J., 1990. Conservative behaviour in the response of crops to water and light. In: R. Rabbinge, J. Goudriaan, H. van Keulen, F.W.T. Penning de Vries and H.H. van Laar (Editors), Theoretial production ecology: reflections and prospects. Pudoc, Wageningen, pp. 3–16.

Moore, C.S., 1978. Biometrical relationships in apple trees. J. Hortic. Sci., 53: 45–51.

Myneni, R.B., 1991. Modeling radiative transfer and photosynthesis in three-dimensional vegetation canopies. Agric. For. Meteorol., 55: 323–344.

Nonhebel, S., 1993. The importance of weather data in crop growth simulation models and assessment of climatic change effects. Thesis, Agric. Univ., Wageningen, 144 pp.

Norman, J.M. and Welles, J.M., 1983. Radiative transfer in an array of canopies. Agron. J., 75: 481–488.

Oker-Blom, P. and Kellomäki, S., 1983. Effect of grouping of foliage on the within-stand and within-crown light regime: comparison of random and grouping canopy models. Agric. Meteorol., 28: 143–155.

Oker-Blom, P., Kaufmann, M.R. and Ryan, M.G., 1991. Performance of a canopy light interception model for conifer shoots, trees and stands. Tree Physiol., 9: 227–243.

Österreicher, J., 1989. Das V-System. Obstbau Weinbau, 10: 268–269.

Palmer, J.W., 1977a. Light transmittance by apple leaves and canopies. J. Appl. Ecol., 14: 505–514.

Palmer, J.W., 1977b. Diurnal light interception and a computer model of light interception by hedgerow apple orchards. J. Appl. Ecol., 14: 601–614.

Palmer, J.W., 1981. Computed effects of spacing on light interception and distribution within hedgerow trees in relation to productivity. Acta Hortic., 114: 80–88.

Palmer, J.W., 1986. Light interception and dry matter production by apple orchards. In: A.N. Lakso and F. Lenz (Editors), The regulation of photosynthesis in fruit trees. NY St. Agric. Exp. Sta., Geneva, New York, pp. 24–27.

Palmer, J.W., 1987. The measurement of leaf area in apple trees. J. Hortic. Sci., 62: 5–10.

Palmer, J.W., 1988. Annual dry matter production and partitioning over the first 5 years of a bed system of Crispin/M.27 apple trees at four spacings. J. Appl. Ecol., 25, 569–578.

Palmer, J.W., 1989a. Canopy manipulation for optimum utilization of light. In: C.J. Wright (Editor), Manipulation of Fruiting. Butterworths, London, pp. 245–262.

Palmer, J.W., 1989b. The effect of row orientation, tree height, time of year and latitude on light interception and distribution in model apple hedgerow canopies. J. Hortic. Sci., 62: 137–145.

Palmer, J.W., 1993. Recent developments on light and fruit tree canopies. Acta Hortic., 349: 99–109.

Palmer, J.W. and Jackson, J.E., 1973. Light interception by bed systems of Cox on M27. East Malling Res. Sta., Ann. Rep. 1972, pp. 55–56.

Palmer, J.W. and Jackson, J.E., 1977. Seasonal light interception and canopy development in hedgerow bed system apple orchards. J. Appl. Ecol., 14: 539–549.

Palmer, J.W. and Wertheim, S.J., 1981. Effects of tree density on fruit quality. Acta Hortic., 114: 139.

Palmer, J.W., Avery, D.J. and Wertheim, S.J., 1992. Effect of apple tree spacing and summer pruning on leaf area distribution and light interception. Scientia Hortic., 52: 303–312.

Palmer, J.W., Bünemann, G., Sansavini, S., Wagenmakers, P.S. and Winter, F., 1989. The international planting systems trial. Acta Hortic., 243: 231–241.

Pearce, S.C. and Doberšek-Urbanc, S., 1967. The measurement of irregularity in growth and cropping. J. Hortic. Sci., 42: 295–305.

Penning de Vries, F.W.T., 1975. The cost of maintenance processes in plant cells. Ann. Bot., 39: 77–92.

Penning de Vries, F.W.T. and Laar, H.H. van, 1982. Simulation of growth processes and the model BACROS. In: F.W.T. Penning de Vries and H.H. van Laar (Editors), Simulation of plant growth and crop production, Pudoc, Wageningen, pp. 114–135.

Preston, A.P., 1956. Orchard tree spacing in relation to wind and cropping. J. Hortic. Sci., 31: 303–306.

Priestley, C.A., 1963. The carbohydrate resources of young apple-trees under four levels of illumination. Ann. Bot., 27, 107: 435–446.

Priestley, C.A., 1981. Perennation in woody fruit plants and its relationship to carbohydrate turnover. Ann. Appl. Biol., 98: 548–552.

Proctor, J.T.A., Kyle, W.J. and Davies, J.A., 1975. The penetration of global solar radiation into apple trees. J. Amer. Soc. Hortic. Sci., 100: 40–44.

Proctor, J.T.A., Watson, R.L. and Landsberg, J.J., 1976. The carbon budget of a young apple tree. J. Amer. Soc. Hortic. Sci., 101: 579–582.

Pukkala, T., Becker, P., Kuuluvainen, T. and Oker-Blom, P., 1991. Predicting spatial distribution of direct radiation below forest canopies. Agric. For. Meteorol., 55: 295–307.

Rabbinge, R., 1976. Biological control of fruit-tree red spider mite. Pudoc, Wageningen, 228 pp.

Reichel, M. and Schmidt, G., 1986. Fruchtmasse und Geschmack der Fruchte von 'Gelber Kostlicher' und 'Auralia' in Abhängigkeit von einigen Einflussfaktoren in der Zeit zwischen Vollblute und Ernte. Gartenbau, 33: 303–305.

Reinhoudt, K., 1986. De V-haag bij peren. De Fruitteelt, 76(4): 98–99.

Robinson, T.L. and Lakso, A.N., 1989. Light interception, yield and fruit quality of 'Empire' and 'Delicious' apple trees grown in four orchard systems. Acta Hortic., 243: 175–184.

Robinson, T.L. and Lakso, A.N., 1991. Bases of yield and production efficiency in apple orchards. J. Amer. Soc. Hortic. Sci., 116: 188–194.

Robinson, T.L., Lakso, A.N. and Carpenter, S.G., 1991. Canopy development, yield, and fruit quality of 'Empire' and 'Delicious' apple trees grown in four orchard production systems for ten years. J. Amer. Soc. Hortic. Sci., 116: 179–187.

Robinson, T.L., Seeley, E.J. and Barritt, B.H., 1983. Effect of light environment and spur age on 'Delicious' apple fruit size and quality. J. Amer. Soc. Hortic. Sci., 108: 855–861.

Robinson, T.L., Wünsche, J. and Lakso, A., 1993. The influence of orchard system and pruning severity on yield, light interception, conversion efficiency, partitioning index and leaf area index. Acta Hortic., 349: 123–127.

Rom, C.R., 1991. Light thresholds for apple tree canopy growth and development. HortSci., 26: 989–992.

Rom, C.R. and Ferree, D.C., 1984a. The influence of light environment early in the season on bloom, fruit development, and return bloom. Fruit Crops 1984: A summary of research. Ohio State Univ., Wooster, Res. Circ., 283: 9–17.

Rom, C.R, and Ferree, D.C., 1984b. A comparison of the influence of summer pruning at two dates on the growth and development of young apple and peach trees. Fruit Crops 1984: A summary of research. Ohio State Univ., Wooster, Res. Circ., 283: 44–48.

Rüger, H., 1989. Wirtschaftlichkeit von Mehrreihenbeeten mit 'Cox Orange'. Erwerbsobstbau, 31: 162–165.

Russell, G., Jarvis, P.G. and Monteith, J., 1989. Absorption of radiation by canopies and stand growth. In: G. Russell, B. Marshall and P.G. Jarvis (Editors), Plant canopies: their growth, form and function. Soc. Exp. Biol., Seminar Series, 31. Cambridge Univ. Press, pp. 21–39.

Sansavini, S., 1975. Palmette and other pruning-training systems for pear trees. In: T. van de Zwet and N.F. Childers (Editors), The pear. Hortic. Publ., Gainesville, Florida, pp. 331–353.

Sansavini, S., Bassi, D. and Giunchi, L., 1981. Tree efficiency and fruit quality in high-density apple orchards. Acta Hortic., 114: 114–136.

Saure, M., 1985. Der Einfluss von Schnittzeitpunkt und Schnittintensität auf Wachstum und Wuchsleistung junger Apfelbäume. Erwerbsobstbau, 27: 169–173.

Saure, M.C., 1987. Summer pruning effects in apple- a review. Scientia Hortic., 30: 253–282.

Saure, M.C., 1990. External control of anthocyanin formation in apple. Scientia Hortic., 42: 181–218.

Schechter, I., Elfving, D.C. and Proctor, J.T.A., 1991. Apple tree canopy development and photosynthesis as affected by rootstock. Can. J. Bot., 69: 295–300.

Scholtens, A., 1990. Enkele rij evengoed als drierijen. De Fruitteelt, 80 (28): 18–19.

Siegrist, J.P., 1984. Pommier: rendement et qualité. Rev. Suisse Vit. Arbor. Hortic., 16 (6): 319–325.

Soest, W. van and Robijn, W.J., 1948. De fruitteelt in Zeeland. In: Vijftig jaar Nederlandse fruitteelt. Uitg. Contact-Agrarisch Fonds, Amsterdam, pp. 59–72.

Spitters, C.J.T., Keulen, H. van and Kraalingen, D.W.G. van, 1989. A simple and universal crop growth simulator: SUCROS89. In: R. Rabbinge, S.A. Ward and H.H. van Laar (Editors), Simulation and systems management in crop protection. Pudoc, Wageningen, pp. 147–181.

Spitters, C.J.T., Toussaint, H.A.J.M. and Goudriaan, J., 1986. Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis. I. Components of incoming radiation. Agric. For. Meteor., 38: 217–229.

Sritharan, R. and Lenz, F., 1988. Effects of water stress in apple. I. Effect of water supply on flower formation and fruit set of the apple cultivar 'Golden Delicious'. Gartenbauwiss., 53: 223–226.

Sugar, D. and Buskirk, P. van, 1991. Trellis and training systems for Bosc pears: first 5 years. Good Fruit Grower, 42 (3): 24–26.

Taylor, B.H. and Ferree, D.C., 1981. The influence of summer pruning on photosynthesis, transpiration, leaf abscission, and dry weight accumulation of young apple trees. J. Amer. Soc. Hortic. Sci., 106: 389–393.

Taylor, B.H. and Ferree, D.C., 1984a. The influence of summer pruning and cropping on growth and fruiting of apple. J. Amer. Soc. Hortic. Sci., 109: 19–24.

Taylor, B.H. and Ferree, D.C., 1984b. Response of apple shoots, flowers, fruits and roots to heading-back summer pruning. Fruit Crops 1984: A summary of research. Ohio Sta. Univ., Wooster, Res. Circ., 283: 38–44.

Thornley, J.H.M. and Johnson, I.R., 1990. Plant and crop modelling. Clarendon Press, Oxford, pp. 3–15.

Tombesi, A. and Belleggia, S., 1986. L'influenca dell'intensità di illuminazione della chiome sulla differenziazone delle gemme a fiore e sulla qualità delle pesche, cv "Flavorcrest". Rivista Ortoflorofrutticoltura Ital., 70: 297–306.

Tréfois, R., 1989. Les sujets porte-greffe pour cérisiers de la Station des Cultures Fruitières et Maraichères de Gembloux. Le Fruit Belge, 57: 215–234.

Tromp, J., 1984. Flower-bud formation in apple as affected by air and root temperature, air humidity, light intensity, and day length. Acta Hortic., 149: 39–47.

Tromp, J., 1994. De invloed van de snelheid van vruchtontwikkelig in het begin van het seizoen op de minerale samenstelling van de vrucht. Jaarverslag 1993, Proefstation voor de Fruitteelt, Wilhelminadorp, pp. 104–105.

Tustin, S., Hurst, P., Warrington, I. and Stanley, J., 1989. Light distribution and fruit quality through multi-layered trellis apple canopies. Acta Hortic., 243: 209–212.

Vandenende, B. and Chalmers, D.J., 1983. The Tatura trellis as a high density system for pear trees. HortSci., 18: 946.

Verheij, E.W.M., 1972. Competition in apple, as influenced by Alar sprays, fruiting, pruning and tree spacing. Comm. Agric. Univ., 72–4, Wageningen, 54 pp.

Verheij, E.W.M. and Verwer, F.L.J.A.W., 1972. Yield density relations for apple trees on a dwarfing and a semi-dwarfing rootstock. Neth. J. Agric. Sci., 20: 58–66.

Verheij, E.W.M. and Verwer, F.L.J.A.W., 1973. Light studies in a spacing trial with apple on a dwarfing and a semi-dwarfing rootstock. Scientia Hortic., 1: 25–42.

Vittrup Christensen, J., 1976. Tree density and double row system in apple orchard. Tidsskr. Planteavl, 80: 603–619.

Vittrup Christensen, J., 1979. Effect of density, rectangularity and row orientation on apple trees, measured in a multivariated experimental design. Scientia Hortic., 10: 155–165.

Wagenmakers, P.S., 1988. Effects of planting system, tree shape, and additional summer pruning on growth, production and flowering of apple trees at high plant densities. J. Hortic. Sci., 63: 383–392.

Wagenmakers, P.S., 1989a. Productivity, growth and light interception in the ISHS planting systems trial in The Netherlands. Acta Hortic., 243: 249–252.

Wagenmakers, P.S., 1989b. High-density planting system trial with pear. Acta Hortic., 243: 303–307.

Wagenmakers, P.S., 1989c. Meer licht met lampen of reflecterend materiaal. De Fruitteelt, 79 (18): 65.

Wagenmakers, P.S., 1990a. Plantsysteem en plantdichtheid. In: S.J. Wertheim (Editor), De Peer. Proefstation voor de Fruitteelt, Wilhelminadorp, pp. 193–202.

Wagenmakers, P.S., 1990b. Planting-systems trial with apple: arrangement and tree height. Ann. Rep. 1989, Res. Sta. Fruit Growing, Wilhelminadorp, pp. 24–27.

Wagenmakers, P.S., 1991a. De toekomst is vierkant. De Fruitteelt, 81 (3): 17–19.

Wagenmakers, P.S., 1991b. Planting systems for fruit trees in temperate climates. Crit. Rev. Plant Sciences, 10: 369–385.

Wagenmakers, P.S., 1991c. Simulation of light distribution in dense orchard systems. Agric. For. Meteorol., 57: 13–25.

Wagenmakers, P.S., 1993. Planting systems trial with Elstar. Ann. Rep. 1992, Res. Sta. Fruit Growing, Wilhelminadorp, pp. 30–32.

Wagenmakers, P.S. and Callesen, O., 1989. Influence of light interception on apple yield and fruit quality related to arrangement and tree height. Acta Hortic., 243: 149–158.

Wagenmakers, P.S. and Tazelaar, M., 1994. Plantdichtheid, rangschikking en lichtbenutting in intensieve beplantingen. Jaarverslag 1993, Proefstation voor de Fruitteelt, pp. 42–48.

Wagenmakers, P.S., Boomgaard, J. van den and Bootsma, J., 1994. Meeste goed gekleurde appels bij 6000 bomen per ha. Fruitteelt, 84(32): 22–23.

Weiss, A. and Norman, J.M., 1985. Partitioning solar radiation into direct and diffuse, visible and near-infrared components. Agric. For. Meteorol., 34: 205–213.

Werth, K., 1981. Development and current achievements of high density plantings in Italy, Switzerland, Austria, and Yugoslavia. Acta Hortic., 114: 295–299.

Wertheim, S.J., 1970. The training of the slender spindle of four apple varieties. Proefstation voor de Fruitteelt, Wilhelminadorp, Publ. No. 10, 158 pp.

Wertheim, S.J., 1977. Van boerenboomgaard naar beddenteelt. De Fruitteelt, 67: 1474–1482.

Wertheim, S.J., 1978. Plantsysteem en vruchtkwaliteit. De Fruitteelt, 68: 200–204.

Wertheim, S.J., 1981. High-density planting, development and current achievements in The Netherlands, Belgium, and West Germany. Acta Hortic., 114: 318–327.

Wertheim, S.J., 1983. Het plantsysteem bij appel, wederom bekeken. De Fruitteelt, 73: 268–273.

Wertheim, S.J., 1984. Teelttechnische aspecten van het plantsysteem. De Fruitteelt, 74: 630–634.

Wertheim, S.J., 1985. Productivity and fruit quality of apple in single-row and full-field plantings. Scientia Hortic., 26: 191–208.

Wertheim, S.J., 1990. Dutch planting and training systems for apples. NY Sta. Hortic. Soc., Proc. Ann. Meeting, Vol. 135, pp. 27–36.

Wertheim, S.J. and Lemmens, J.J., 1973. Over het plantsysteem bij appel en peer. Med. nr. 12, Proefstation voor de Fruitteelt, Wilhelminadorp, 77 pp.

Wertheim, S.J., Jager, A.J. de and Duyzens, M.J.J.P, 1986. Comparison of single-row and multi-row planting systems with apple, with regard to productivity, fruit size and colour, and light conditions. Acta Hortic., 160: 243–258.

Wibbe, M., 1991. CO_2-Gaswechsel van Apfelbaumkronen unter Freilandbedingungen in Abhängigkeit von Fruchtbehang und Wasserversorgung. Thesis, Institut für Obstbau und Gemüsebau, Bonn, 120 pp.

Wibbe, M.L., Blanke, M.M. and Lenz, F., 1993. Effect of fruiting on carbon budgets of apple tree canopies. Trees, 8: 56–60.

Widmer, A., Riesen, W., Husistein, A., and Muller, K., 1989. Das Nordhollander Schnitt- und Pflanzsystem. Schweiz. Z. Obst Weinbau, 125 (1): 7–13.

Wijsmuller, J.M. and Wagenmakers, P.S., 1990. Minder snoeien geeft gunstig resultaat. De Fruitteelt, 80 (16): 18–19.

Wilton, W.J.W., 1989. Orchard management factors affecting the performance of New Zealand orchards- an extension viewpoint. Acta Hortic., 240: 151–153.

Wit, C.T. de, 1958. Transpiration and crop yields. Versl. Landbouwk. Onderz., 64.6, Pudoc, Wageningen, 88 pp.

Wit, C.T. de, 1965. Photosynthesis of leaf canopies. Agric. Res. Report No. 663, Pudoc, Wageningen, 57 pp.

Curriculum vitae

Patricia Simone Wagenmakers werd geboren op 15 september 1958 te Zutphen. Na het behalen van het diploma Gymnasium-β aan het Baudartius College te Zutphen begon zij in 1977 de studie biologie aan de Rijksuniversiteit te Utrecht. In juni 1984 werd het doctoraal examen afgelegd met hoofdvak Landschapsoecologie en Natuurbeheer en bijvakken Oecofysiologie en Theoretische Teeltkunde (Landbouwhogeschool Wageningen). Sinds augustus 1984 is zij werkzaam als onderzoeker teelt grootfruit op het Proefstation voor de Fruitteelt in Wilhelminadorp.