*The World's Largest Open Access Agricultural & Applied Economics Digital Library*

# This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

## Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

# A Proposal for a Bioeconomic Model of an Apple Orchard[1]

Susie Hester and Oscar Cacho

Department of Agricultural and Resource Economics
University of New England
Armidale NSW 2350

Contributed paper presented at the 41st Annual Conference of the Australian Agricultural and Resource Economics Society, Pan Pacific Hotel, Gold Coast, 20-25 January 1997

## Abstract

Management of deciduous perennial fruit crops requires a good understanding of the many physiological and horticultural factors that influence tree growth and fruit production. Crucial decisions that must be made include the choice of tree density, tree variety, pruning and training techniques. These choices, some of which are made before the orchard is planted, have implications for grower returns over the life of the orchard because they influence tree growth and fruit quantity and quality.

A dynamic model of an apple tree is developed in this study, with the ultimate goal of simulating apple orchard management decisions in a multi-period setting. The model takes into account the vegetative and reproductive physiology of apple trees, factors affecting apple quality and quantity, and the interrelationships between these factors. The model is designed to allow flexibility in the incorporation of alternative apple cultivars and pruning/training systems. The implementation and importance of these features are discussed in the paper.

## Introduction

The production of large quantities of high quality fruit from an orchard relies on a good understanding of the biological basis of tree and fruit growth. A fruit grower needs to understand how the choice of orchard system and management strategy affects use of inputs in the production process and therefore profitability. The evaluation of alternative orchard management strategies and orchard systems can be significantly aided by simulation models. An appropriate simulation model in the case of an apple orchard would encompass, in significant detail, both the biological and economic processes involved in tree growth and fruit production.

Biologists have developed many models that describe specific aspects of plant and tree growth and much of this work has been applied to perennial tree crops including apples. Included here is the work of Jackson (1981), Jackson and Palmer (1979, 1981) and Palmer (1977) on light interception and canopy design in apple orchards, Brain and Landsberg (1981) who analyse pollination, initial fruit set and fruit drop in apples using

[1] Helpful comments from Dr Phil Simmons are gratefully acknowledged.

mathematical models, and De Wit's (1965) work on modelling photosynthesis and plant growth.

Research into apple production has also been undertaken by economists. In perennial crop research, horticultural economists are often interested in modelling optimal replacement strategies. Studies of this kind have used dynamic linear programming models (Willis and Hanlon, 1976; Knapp 1987), net present value methods (Goedegebure 1988) and maximum sustainable yield techniques (Tisdell and De Silva 1986). Other horticultural economists have investigated the profitability of various orchard systems through budgeting techniques (McKenzie and Rae, 1978) and linear regression (Cahn and Goedegebure, 1992).

Economists modelling optimal replacement decisions in orchards, or general orchard production systems have tended to largely ignore the considerable body of knowledge generated by biologists and other scientists. The use of this knowledge would seem necessary because it allows modellers to generate yield functions that accurately reflect the differences in varieties and manipulation of tree growth that is commonplace in orchard management.

Recognising a gap in horticultural simulation modelling, a preliminary attempt to model apple orchard production using bioeconomic methods is presented in this paper. A brief discussion of important biological concepts in apple tree growth are included in the following section, which describes the management choices facing an apple grower. The bioeconomic model is then developed in several sections.

# The Orchard Management Problem

An apple grower's income depends on the amount and the quality of apples produced. This will largely depend on the selected orchard system, defined as the integration of all the horticultural factors involved in establishing and maintaining a planting of fruit trees (Barritt, 1987). In choosing the preferred orchard system, a large number of choices face the grower.

## Pre-planting Decisions

Orchard managers face complex long-term decisions that interact with daily orchard management. There is a lag of several years between planting and production and choices concerning fruit variety, tree spacing, and pruning and training systems represent long-term commitments that are made before an orchard is planted. Fruit characteristics, the age of bearing (precocity), future market demands and climate suitability are other factors that need to be taken into account when choosing an orchard system. Incorrect choices will be costly, if not impossible, to correct in the short term.

## The Apple Tree

An apple tree is composed of a piece of a particular 'cultivar' (*culti*vated *var*iety) called a scion that is grafted or budded onto a 'rootstock'. This vegetative propagation allows the cultivar to maintain all the characteristics of the original tree. A large number of apple rootstocks and scion varieties have been available to growers for several decades, and each combination has implications for orchard management.

A specific rootstock is normally chosen for the tree size it will produce. The ultimate size of an apple tree can be limited through the use of certain rootstocks. Historically, the most commonly available rootstock produced trees of variable size and performance. In modern orchards, where the size of the apple tree plays a central role in orchard management, and where tree uniformity, precocity and crop efficiency are crucial, most trees are planted on one or more of the clonal rootstocks developed after 1900. The large number of (dwarfing) rootstocks now available means that trees can be grown to achieve almost any size or degree of dwarfness.

The scion section of the apple tree determines the fruit variety and fruit features such as size, shape, colour, flavour, firmness, ripening season, and pest and disease resistance. The rate of scion growth (vigour) is influenced by many factors, including the intrinsic vigour of the scion and the vigour potential of the chosen rootstock. Other factors include climatic variables: temperature, light and rainfall; soil factors such as mineral content and level of soil water; management factors such as pruning, training and weed control; and tree factors such as tree health and crop load (Webster, 1995).

The age at which an apple tree first bears fruit (its precocity) will vary according to the rootstock/scion combination. Important physiological stages in the fruit production process are the formation of flower buds during the previous growing season, adequate chilling of these fruit buds in winter, flowering, pollination and fruit-set of the flowers in the spring, removal of excess fruits (thinning) to maintain good fruit size, fruit maturation, ripening and finally harvest.

During the growing season apple trees and their fruit are subject to damage by a range of disease and insect pests. Fungi, insects and mites are responsible for various types of damage to apple trees, with some diseases and pests able to reinfest several times during a single growing season. Chemical control is available to most common apple orchard diseases and pests. The constant monitoring of trees, good orchard hygiene and prompt application of chemicals are important factors in maintaining healthy apple trees.

## Light

Light is the most important factor in the process known as photosynthesis, a process on which plant growth depends. Good light penetration into an apple tree canopy throughout its growing season is essential, and is especially critical to fruit production. In apples, canopy development has a seasonal and a lifetime developmental pattern.

Light must be able to penetrate the apple tree canopy to the extent that it satisfies the requirements for apple spur flowering and fruit set (Robinson et al., 1991). Light interception and distribution within the tree canopy is also an important influence on the quantity and quality, size and colour, of apples produced (Wagenmakers and Callesen, 1995)

The level of light intercepted by an orchard will depend on many factors including: the amount and arrangement of leaves, fruits and branches within each tree; tree shape and size; the spacing between trees and row orientation; and the angular distribution of light from the sun and sky (Palmer 1981). There are many ways of modifying apple tree canopies to improve light interception and distribution, including the use of rootstocks, scions, pruning and tree training. These four variables alone potentially give numerous tree forms, planting arrangements, tree heights, widths and geometric forms, with the practical value of modifications depending on their effect on orchard production efficiency (Robinson et al. 1991).

## Training and Pruning

Tree size is central to orchard management and fruit production. Apart from the inherent growth characteristics of the scion and rootstocks, tree growth can be manipulated through training and pruning. Techniques that control the shape, size and direction of tree growth are known as training, and the removal of particular parts of the plant are known as pruning. Pruning and training are used to alter the growth and fruiting habits (productivity) of the tree. If left without pruning or training, the result is poor distribution of light throughout the canopy, harvest and spraying difficulty.

The practice of pruning an apple tree occurs throughout its lifetime. An important consequence of tree pruning is that one year's growth remains to influence the growth of succeeding years. In young trees, pruning is undertaken with the aim of training the tree to produce a certain shape and structurally sound framework (Janick, 1986). The framework should be one that is able to hold heavy crops, withstand high winds, allow easy access to the picker and pruner (a smaller tree), allow thorough penetration and tree coverage to orchard sprays, with a shape that allows light to enter all parts of the tree (Hartmann et al., 1988). When well-trained trees reach the age when they begin to form flowers and produce fruit they do so on a strong frame with well distributed 'fruiting wood' around the tree (Hartmann et al., 1988). When this is the case, only moderate annual pruning is necessary.

Training is used to improve light penetration into the apple tree. Robinson et al. (1991) summarise the two approaches on which most training systems are based. The first is to allow the tree to grow to its natural form which allows light penetration through many small openings in the canopy, examples include the multiple leader, central leader, vertical axis, or slender spindle techniques of training a tree. The second approach is to restrict tree canopies to certain geometric forms with fewer large, permanent openings that allow light penetration. Examples of this approach include thin restricted single planes of foliage such as narrow hedgerows, tree walls, and trees trained to the A, V and T forms.

## Tree Density

The choice of planting density is normally based on consideration of the ultimate size of the tree at maturity and whether the rootstock is dwarfing or invigorating. The use of dwarfing rootstocks allows trees to be planted closer together because they will result in very small trees. Thus dwarfing rootstocks allow for higher density tree planting systems to be adopted. The number of trees planted per hectare has implications for the initial investment in trees, input use and per hectare yield of trees.

Low density plantings (300 trees per hectare) do not use dwarfing rootstocks and maintenance labour for pruning and training is minimal. Returns per hectare are lower because yield per hectare is lower and trees may take up to twenty years to reach maximum production.

Pruning and training are much more important tasks for medium to high intensity plantings (1000 trees per hectare). Dwarfing rootstocks are normally used in this system and commercial yields are achieved sooner than with low density plantings.

In high density plantings (1500-2000 trees per hectare) and very intense density planting systems (2000-3500 trees per hectare), the cultivar and rootstock choice are critical for size control. In these systems very dwarfing and dwarfing rootstocks are used and trees are planted very close together. Skilled management is required for training and pruning, and a complete understanding of tree growth and nutrition is essential. Appropriate training systems in very high density plantings include trellis, hedgerow, double row and spindle bush systems. For high density plantings central leader pyramid shaped training is essential (Fleming, 1996).

While initial investment in the trees is higher in high density plantings, a much higher yield is experienced in the early years of orchard operation compared to medium and low density planting systems. Yields of dwarfed trees at maturity are, however, usually less than those from larger trees on intermediate or vigorous rootstocks. Closer planting of dwarf trees and their earlier bearing habits should more than compensate for this loss in yield per tree.

# The Economic Model

Consider an apple orchard of a given area, the objective of the fruit grower is to select and plant an 'optimum mix' of apple tree varieties (stock/scion combinations) using certain pruning and training techniques over time, so as to maximise the discounted value of profit. Prices received for the fruit may differ between time periods in years (t), and for each variety of apple (j). The quantities harvested will also vary with the variety of fruit tree, and with the age (i) of the tree. Costs will vary with the age, variety and time period, and also with the pruning and training techniques employed. Farm level profitability can be assessed using the following economic framework:

The profit function is expressed as:

$$(1) \quad \underset{y}{Max}\,\pi = \sum_{t}\left[\left(\sum_{i}\sum_{j} P_{j,t}\, Q_{i,j,t}\right) - C_t\right]e^{-rt} \qquad (i = 1,..,I),\ (j = 1,..,J),\ (t = 1,..,T),$$

where:

$P_{j,t}$ represents the price of a unit sold of apple variety $j$ in time period t,

$Q_{i,j,t}$ represents the quantity of each variety $j$ that is sold (the 'packout' quantity) from each age group over time,

| $r$ | is the discount rate |
|---|---|

Since not all fruit that is harvested is sold, an additional equation describing the level of 'packout' is added:

(2) $Q_{i,j,t} = h_j H_{i,j,t}$ $\qquad 0 \le h \le 1$

where:

$H_{i,j,t}$ is the total quantity of harvested fruit; and

$h_j$ represents the proportion of harvested fruit that is sold to the fresh fruit market each year. This often varies between varieties. Note that (1-h) gives the level of spoilage, which is not necessarily wasted and may be sold as juicing fruit.

Total harvest is a function the yield (Y):

(3) $H_{i,j,t} = f(Y_{i,j,t})$

where:

$Y_{i,j,t}$ represents total yield for a given age group $i$, variety $j$ and time period $t$

The area planted (A) depends on new plantings (NP) and removals of trees (R) in each period[2]. The area of trees in the first age group of each time period will be equal to the new plantings of all varieties that occur in that time period. In the age groups other than $i = 1$, the area of plantings will be equal to the carryover from the previous period minus any removals from the current stock of trees. No removals occur in age group one.

(4) $A_{i=1,j,k,t} = NP_{j,k,t}$

(5) $A_{i+1,j,k,t} = A_{i,j,k,t} - R_{i+1,j,k,t}$ $\qquad$ (i = 1, 2, 3,.., I-1), (k = 1,...., K)

where:

$R_{i,j,t}$ represents removals of variety $j$ from a particular age group,

$k$ represents a given management (density, pruning, training) system

The area of trees will also be constrained by the size of the farm:

(6) $\sum_i \sum_j \sum_k A_{i,j,k,t} \le KF$ $\qquad$ where KF is farm size in hectares

The yield function ($Y_{i,j,t}$) takes into account a number of biological, physiological and management characteristics of orchard operation. Yields depend on the orchard management system used. Thus for any time period:

(7) $Y_{i,j,t} = \sum_k y_{i,j,k,t} A_{i,j,k,t}$

[2] Equations for plantings and removals are based on those of Knapp (1987)

Yield, $y_{i,j,k}$ will be estimated by a biological model described below.

The cost function includes annual planting costs, labour and other input costs:

$$(8)\quad C_t = \sum_j \sum_k rp_j NP_{j,t} + \mathbf{rz}\mathbf{Z}_t + LC_t$$

where:

| | |
|---|---|
| $rp_j$ | is the price of new trees |
| $\mathbf{rz}$ | is a vector of prices of other inputs |
| $\mathbf{Z}_t$ | is a vector of inputs (fertiliser, chemicals irrigation) |
| $LC_t$ | represent labour costs |

Labour is a critical input and represents a significant proportion of costs in an orchard. Labour requirements for harvesting depend on yield, while labour requirements for other tasks (such as pruning, spraying) depends on the size, shape and number of trees, which in turn depend on the management system, therefore, labour costs are defined as:

$$(9)\quad LC_t = rh\sum_i \sum_j Y_{i,j,t} + rl\sum_i \sum_j \sum_k L_{i,j,k}$$

where

| | |
|---|---|
| $L_{i,j,k}$ | are the labour requirements for age group $i$ and verity $j$ under management system k |
| $rl$ | is the cost of hired labour, and |
| $rh$ | is the cost of harvesting labour |

The economic model allows selection of an optimal mix of fruit tree varieties. The optimal mix will be selected through information on yield of each tree variety under alternative management systems. Yield information will be estimated by the biological model described in the next system.

## The Biological model

Horticultural management models of apple orchards normally investigate economic aspects of production without including important biological relationships that have been developed over the years by biologists and other scientists. These biological relationships can allow modellers to generate yield functions that reflect varietal differences, climatic factors, lifetime and seasonal growth patterns, and canopy manipulation techniques that are common considerations in realistic orchard management.

Winter (1976) and Thiele and Zhang (1992) developed orchard models however, their models do not provide the information required for the model described here, therefore a simplified biological model will be used, as described in this section. Central to the biological model developed below is the description of photosynthesis, and how its products are allocated within an apple tree (see Figure 1).

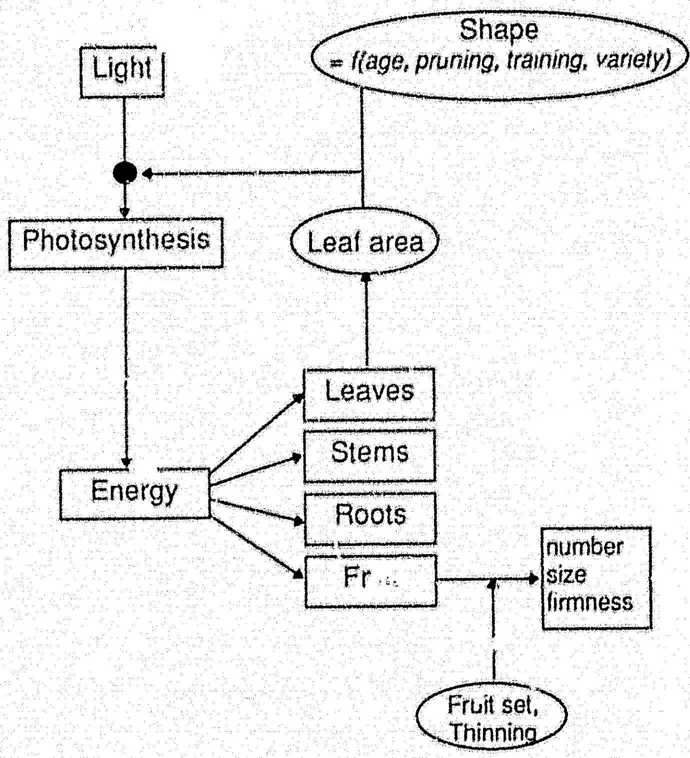


Figure 1

The amount of photosynthesis undertaken by the tree is influenced by the amount of light it intercepts, which in turn is influence by the shape of the tree. The shape of the tree varies with its age, pruning and training techniques used and the particular time of season. The products of the photosynthetic process are allocated between the leaves, old and new stem, the roots, and fruit. Whether or not a tree is producing fruit has a significant effect on this allocation process.

Canopy photosynthesis ($P_c$) is the sum of the photosynthesis of the leaves ($P_l$) which make up the canopy, and depends on the photosynthetic capacity of the leaves within the canopy and the light attenuation and interception properties of the canopy (Johnson, 1994):

$$(10) \quad P_c = \int_0^l P_l \, dl$$

where

$l$ is the leaf area index

Le f photosynthesis can be described by a number of equations, the most frequently used equation (France and Thornley, 1984), a rectangular hyperbola, is employed in this analysis:

$$(11) \quad P_l = \frac{\alpha I_l P_{max}}{\alpha I_l + P_{max}}$$

where

- $I_l$ represents the level of irradiance intercepted by leaves
- $P_{max}$ is the value of P at saturating light levels
- $\alpha$ is a constant that measures the efficiency of leaf photosynthesis

Measuring light interception and attenuation by a row crop is more difficult because of the discontinuous nature of the canopies. Canopy shapes become difficult to model and light interception is affected by the rows between trees. A well accepted equation describing light interception by leaves in discontinuous canopies (Thornley and Johnson, 1990) is :

$$(12) \quad I_l = \left(\frac{k}{1-m}\right) I_0 e^{-kl'}$$

where

- $I_0$ is the irradiance above the canopy
- $k$ is the light extinction coefficient for a given canopy depth
- $m$ is the transmission coefficient of the leaf
- $l'$ is the cumulative leaf area index, measured per unit of potentially shaded surface area

Photosynthates, the products of photosynthesis, are used by various parts of the tree in the process of growth and development. This process is represented as:

$$(13) \quad DM = (\theta_L + \theta_F + \theta_R + \theta_S) P_c \gamma$$

where

- $\theta_x$ represents the proportion of new growth achieved by each part of the tree (leaves, fruit, roots and stem),
- $\gamma$ is a conversion factor between photosynthesis and dry matter, and

$P_c$ is described as in (13). Notice that the proportions $\theta_x$ must all sum to 1.0.

A major task in this modelling effort is the estimation of model parameters for different varieties of trees and orchard management systems.

## Model Solution and Applications

The biological model developed in this paper details the basic photosynthetic process in apple tree growth. It allows for differences in variety and for pruning and training techniques, through the effect of tree shape on light interception.

The bioeconomic model will be solved in two stages. First, the biological model will be used to produce a multidimensional table of yields and labour requirements for each variety, age group and management system. The economic model will then use the table to determine optimal strategies under alternative price conditions. The economic model may be implemented either as a multiperiod mathematical programming model or as a dynamic programming model.

Once implemented, the biological model will be attached to the economic model through the yield function. The bioeconomic model will then be used to assess optimal orchard management strategies under various tree growth and tree management strategies, and various demand conditions.

The bioeconomic model will ultimately be used to simulate the effects of various types of research on orchard profitability. Many types of apple orchard research are currently funded, with little knowledge on how funds should be divided between certain categories. Research areas currently receiving funding include Pest, Disease and Weed Management; Varietal Improvement; Soil, Nutrition and Irrigation; Technology Transfer; Industry Statistics; Production Systems; Disinfection; Total Business Management; Fruit Quality Management; New Products; and Storage. The effect of various types of research on farm level profit will then be simulated through the manipulation model parameters.

The biological model can be extended to analyse pollination, fruit set, fruit growth and development for different varieties and management strategies. The economic model can be extended to include off farm sectors that influence orchard returns, such as storage, transport and demand sectors.

## Conclusion

While several authors have attempted the integration of economic and biological information into models of apple orchard management, a model that captures growth characteristics of many varieties simultaneously and links this information with production and demand factors is lacking. The model described in this paper is the first stage of an attempt to use detailed biological and economic information to evaluate the effects of alternative management strategies, orchard systems and research programs on grower returns.

## References


Barritt, B. H. (1987), 'Orchard Systems Research with Deciduous Trees: A Brief Introduction', *HortScience*, 22(4), 548-549.

Brain, P. and Landsberg, J. J. (1981), 'Pollination, initial fruit set and fruit drop in apples: analysis using mathematical models', *Journal of Horticultural Science*, 56(1). 41-54.

Cahn, M. B. and Goedegebure, J. (1992), 'Economic aspects of apple production in relation to tree density', *Journal of Crop and Horticultural Science*, 20, 289-296.

De Wit, C. T. (1965), 'Photosynthesis of Leaf Canopies', Agricultural Research Report 663, PUDOC, Wageningen, The Netherlands, 57 pp.

Fleming, D. (ed) (1996), *Deciduous Tree Fruit Cultivars. Growers' Reference Guide*, Fleming's Nurseries, Monbulk, Victoria, second edition.

France, J. and Thornley, J. H. M. (1984), 'Mathematical Models in Agriculture, Butterworths, London.

Goedegebure, J. (1988), 'A calculation model for investments in perennial plantings', *Acta Horticulturae*, 223, 159-165

Hartmann, H. T., Kofranek, A. M., Rubatzky, V. E. and Flocker, W. J. 1988, *Plant Science: Growth, Development and Utilization of Cultivated Plants*, 2nd edn, Prentice Hall, New Jersey.

Jackson, J. E. (1981), 'Theory of light interception by orchards and a modelling approach to optimising orchard design', *Acta Horticulturae*, 114, 69-79.

Jackson, J. E. and Palmer, J. W. (1981), 'Light Distribution in Discontinuous Canopies: Calculation of Leaf Areas and Canopy Volumes Above Defined 'Irradiance Contours' for use in Productivity Modelling', *Annals of Botany*, 47, 561-565.

Jackson, J. E. and Palmer, J. W. (1979), 'A simple model of Light Transmission and Interception by Discontinuous Canopies', *Annals of Botany*, 44, 381-383.

Janick, J. 1986, *Horticultural Science*, 4th edn, W. H. Freeman and Company, New York.

Johnson, I. R. (1994), PLANTMOD 2.1: Exploring the Physiology of Plant Communities, Greenhat Software, Armidale, Australia.

Knapp, K. C. (1987), 'Dynamic Equilibrium in Markets for Perennial Crops' *American Journal of Agricultural Economics*, 69(1).

McKenzie, D. W. and Rae, A. N. (1978), 'Economics of High Density Apple Orchards', *Acta Horticulturae*, 65, 41-46.

Palmer, J. W. (1977), 'Diurnal Light Interception and a Computer Model of Light Interception by Hedgerow Apple Orchards', *Journal of Applied Ecology*, 14, 601-614.

Robinson, T. L., Lakso, A. N. and Ren, Z. 1991, 'Modifying Apple Tree Canopies for Improved Production Efficiency', *HortScience*, vol. 26, no. 1, pp. 1005-1012.

Thiele, G. F. and Zhang, J. (1992), 'The Dynamic Apple Tree System: Relationships to Aid Management Strategies', Acta Horticulturae, 313, 249-255.

Thornley, J. H. and Johnson, I. R. (1990), *Plant and Crop Modelling: A Mathematical Approach to Plant and Crop Physiology*, Oxford University Press, New York.

Tisdell, C. A. and De Silva, N. T. M. H. (1986), 'Supply-Maximising and Variation-Minimising Replacement Cycles of Perennial Crops and Similar Assets: Theory Illustrated by Coconut Cultivation', *Journal of Agricultural Economics*, 37(2), 243-51.

Wagenmakers, P. S. and Callesen, O. (1995), 'Light distribution in apple orchard systems in relation to production and fruit quality', *Journal of Horticultural Science*, 70(6), 935-948.

Webster, A. D. 1995, 'Rootstock and interstock effects on deciduous fruit tree vigour', *New Zealand Journal of Crop and Horticultural Science*, vol. 23, pp. 373-382.

Willis, C. and Hanlon, W. (1976), 'A Temporal Model for Long-Run Orchard Decisions', *Canadian Journal of Agricultural Economics*, 24(3), 17-28.

Winter, F. (1976), 'A Simulation Model for Studying the Efficiency of Apple and Pear Orchards', Gartenbauwissenschaft, 41(.), 26-34.