

Modelling apple orchard systems

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Abstract

While a number of models have been developed to assist managers of deciduous fruit tree crops with specific aspects of decision making, most are non-optimising predictive models and few employ detailed mechanistic models of fruit-tree growth that would enable the simulation of any orchard system from planting to maturity. This paper details the complex biological and economic relationships present in an apple orchard system and describes a dynamic simulation model based on these interactions. The model is bioeconomic in nature, and may be used to investigate a range of issues of relevance to the commercial apple orchardist. These issues include understanding how biological factors influence apple-tree productivity, and how to choose among a diverse range of apple orchard systems. Each system, consisting of a particular combination of cultivar, rootstock, tree spacing and training method, has implications for fruit quality, quantity and ultimately profit. The choice of system is made at planting, while an important annual decision is the optimal rate of thinning, both of which determine potential yield over the lifetime of the orchard. These decisions also influence costs and revenues per hectare and, by necessity, are made in the context of unknown future prices of inputs and outputs. The bioeconomic model is used to maximise net present value of one orchard system by selecting optimal thinning strategies over a 15 year period.

Keywords: Horticulture; Bioeconomics; Modelling; Thinning; Apples

1. Introduction

Orchard systems are complex. Managers of deciduous perennial fruit crops must consider both biological and economic relationships in determining preferred orchard design and life-time orchard management strategies. Decisions about variety, tree size and varietal mix made at planting determine potential yield over the lifetime of the orchard. These decisions also influence costs and profit per hectare and, by necessity, are made in the context of unknown future prices of inputs and outputs. Once trees are bearing fruit, the decision concerning the amount of fruit to leave on the tree until harvest remains one of the few ways that the value of the annual orchard yield may be influenced.

A simulation model representing the apple orchard is a particularly useful means of evaluating the effects on yield and profitability of alternative orchard systems and other decisions under the direct control of the orchardist. Given the

importance of biological and economic components in orchard profitability, both elements should feature in the model if the orchard system is to be adequately described and simulations meaningful. Lack of data on yields of many important apple varieties overtime means it is necessary to adopt a “bioeconomic approach”.

A bioeconomic model consists of a biophysical model, which describes a production system, and an economic model that relates the production system to market prices and resource constraints. The economic model provides the link between the market and the production system and controls the operation of the biophysical model by controlling inputs and obtains feedback from the biophysical model as outputs (Cacho, 1997). If the economic model is designed as an iterative optimisation model, the input-output cycle might occur thousands of times, with inputs being adjusted in response to outputs until an optimal solution is obtained (Cacho, 1997).

Once developed, an important use of bioeconomic models is simulation. Simulation models of agricultural systems have grown in popularity in recent decades due to their usefulness in tackling the inherent dynamic and/or stochastic nature of agricultural problems and due to increased computer capacity (Oriade and Dillon, 1997). Simulation may substitute for large-scale physical experimentation, which could otherwise take decades, especially in the case of perennial crops.

A bioeconomic model can be a systems model that includes economic components or a multiequation model with a single equation representing the biological system (Cacho, 1997). The biological simulation models that underlie bioeconomic models may vary considerably in their complexity and depend critically on the purpose for which they are constructed. The biological simulation models developed by biologists and agricultural scientists are often too detailed to be used in optimising economic models designed by economists. Conversely, simulation models developed by economists tend to be too simple

by biologist's standards with models consisting of linear or simple non-linear functions to allow for solution of optimisation problems (Cacho, 1997). Bioeconomic models may be developed using either non-optimising (positive) or optimising (normative) frameworks. Optimising models provide the decision maker with courses of action that will lead to the optimisation of a particular criterion, while non-optimising, positive models, indicate outcomes resulting from alternative decisions.

2. Review of bioeconomic modelling in deciduous fruit tree research

Despite the development of a large number of bioeconomic models for use in management of annual crops (see Penning de Vries and van Laar, 1982; Oriade and Dillon, 1997), models are not available for perennial tree-crop research of the type described in this paper. Instead, a large number of biophysical models and biological models that describe particular aspects of individual apple-tree growth and fruit production have been developed and only a few have been used in conjunction with an economic modelling framework. While modelling of perennial crops undertaken by economists include yield estimates, these are rarely the output of detailed simulation models. It is most common for yield functions to be estimated from experimental data or survey information. These models and those developed by biologists which contain simple economic relationships are all loosely described as bioeconomic models in this section.

Bioeconomic models developed by economists to analyse issues in perennial-crop research commonly use both non-optimising and optimising frameworks. Maximising the discounted value of profits (NPV) subject to aspects of orchard operation, including optimal replacement of trees and optimal mix of tree varieties, are typical objectives of these models. Non-optimising models tend to assess profit outcomes resulting from a narrowly defined set of alternative management strategies.

Biologists and horticulturists also use optimising and non-optimising bioeconomic models of perennial-orchard operation. These models typically use simple economic models attached to well developed biophysical models to analyse specific aspects of fruit production and orchard management, normally for a single growing season. Aspects of management include alternative thinning strategies and their effects on orchard returns (Thiele and Zhang, 1992; Johnson and Rasmussen, 1990).

Table 1 presents a chronological review of bioeconomic models developed for analysis of deciduous perennial tree crops. The list is not exhaustive; rather, it represents trends in deciduous fruit tree research by both horticulturists and economists. While the models used are described as bioeconomic in scope, it is acknowledged that many bioeconomic modellers would preclude several of these models from this category because they are without some well defined economic and/or biological elements.

In general, it appears that the apple is a popular deciduous fruit tree for modelling purposes. Researchers have employed simple empirical biophysical models to describe fruit orchards and specific aspects of fruit production, although detailed bioeconomic models of orchard management are largely missing from the research. A large number of simulation models are developed as decision support tools for growers. While simulation features prominently as the chosen analysis technique, dynamic programming, mathematical programming and cost-benefit analysis techniques are also used. Orchard replacement policies and fruit variety mix are the most common decision variables. Other decision variables include planting density, fruit load, capital borrowings, rootstock, pest number and use of hail netting. Profit maximisation and/or profit simulation is the most common objective of the modelling work.

Willis and Hanlon (1976) and Graham et al. (1977) are examples of research using linear programming to analyse orchard profitability. Neither paper employs a detailed biophysical model. Rather, data on apple-tree yields gained

from survey information are used to generate yield coefficients. Willis and Hanlon (1976) develop an analytical framework for achieving, over time, an optimal mix of apple varieties for a case-study farm. Their framework considers alternative goals such as minimum acceptable family living standards and maximum acceptable risk using a lexicographic approach.

Graham et al. (1977) also take a case study approach in determining the optimal mix of fruit trees for a given orchard. Single-and multi-period linear programming models are used to determine optimal renewal strategies and combinations of fruit enterprises (cherry, apple and pear) through comparisons of life-time profitability.

Winter (1976, 1986) develops one of the most detailed bioeconomic models of an apple orchard in the literature. Called FRUPRO, it is used to compare profitability of various apple and pear orchard systems. The biological component of the model is based on a yield-forecast system. All elements of yield are influenced by a series of genetic and ecological parameters that vary by variety and orchard area respectively. The annual development of trees and their yields are calculated for the assumed 30 years of productive life. FRUPRO allows the user to investigate the effects of decision variables, including different planting systems, prices and wages, on endogenous variables including yield, costs, income and profitability. FRUPRO has been used by other researchers to investigate orchard replacement (Buchwald, 1986) and orchard profitability (Gross and Rais, 1986).

Optimal replacement is analysed using a dynamic programming framework in Childs et al. (1983). The empirical biological model consists of a series of yield curves for several cultivar/rootstock and age combinations. A quadratic function is used to estimate the yield curves from survey data of New York apple orchardists.

The dynamic programming model maximises the net present value of after-tax cash flow from selected replacement strategies. The dynamic programming

model is initialised by defining five policies: keep the current orchard; replace with standard trees; replace with semi-dwarf trees; replace with interstem trees (which removes the need for support); and replace with dwarf trees. Childs et al. (1983) use the Howard approach to dynamic programming, which in turn uses the Policy Iteration method for finding an optimal solution.

Studies by Haley et al. (1990) and Groot (1996) examine pest control strategies in apple and pear orchards using simulation models. Haley et al. (1990), a team consisting of a researcher, a pest manager and a computer scientist, develop a decision-support model that assesses the benefits of pest control in apple orchards. The model identifies the potential success of biological control for the pest in question, benefits and costs of pest control and possible side effects of using a particular pesticide. Benefits of pest control are determined by assessing crop value, likely damage inflicted by the pest and efficacy of the pesticide used. The decision support model developed by Groot (1996) uses an empirical model to calculate the economic and ecological consequences for a fruit farm of using different crop protection strategies. The context of the study is the legislated reduction in the use of farm chemicals in Dutch agriculture by 44 per cent in the year 2000 compared to the 1984-88 levels.

Johnson and Rasmussen (1990) and Thiele and Zhang (1992) are also interested in a single aspect of fruit production – fruit size. Given that large-sized fruit are more valuable than small fruit, it is common practice for orchardists to remove a number of fruit from the tree in order to improve average fruit size of those that remain. Johnson and Rasmussen (1990) investigate the optimal economic fruit load for peach trees. The relationship between average peach size and fruit number per tree is estimated using linear regression, then individual fruit weights are fitted to a normal distribution around the mean weight. Prices for various fruit sizes and variable costs of running a peach orchard make up the economic model and optimal fruit load is defined as that level where maximum net revenue occurs. The authors only consider one growing season and provide

no guidance on lifetime thinning strategies that might be useful to apple thinning.

Thiele and Zhang (1992) develop a model that is also aimed at measuring the relationship between thinning and crop value. Their model is developed as a decision support tool for apple orchardists and requires growers to enter their own biological data by counting flower and fruit numbers during the season, and to enter labour, material and machinery usage for their operation. The model provides for four alternative management strategies: (i) planning from the flowering period; (ii) planning from the fruit number, before thinning but after fruit set; (iii) planning after thinning when final fruit number is known; and (iv) assessing financial strategies by testing various price levels. Each strategy requires different information from the grower. The empirical biophysical model is used to simulate gross margins for alternative thinning strategies based on the timing and severity of thinning in a given year. While the authors acknowledge the dynamic and perennial nature of the apple tree and the issue of interaction between one year and the next, a correction factor for biennial influence was not included in the model.

The aim of the simulation model developed by Cahn et al. (1997) is decision support. The model predicts the economic outcomes for different planting strategies and includes the age at which apples are left on the tree for the first commercial harvest. The biological model is empirical and uses data from trials and other research to develop relationships between planting strategies, inputs and outputs. The computer model predicts the economic outcomes of one hectare of apples for four decision scenarios.

Whitaker and Middleton (1999) use cost-benefit analysis to determine the profitability of hail netting for various apple varieties in high-density plantings. The authors analyse profitability of hail netting assuming the high-density orchard systems are all replaced after their fifteenth year. Orchard yields with

and without hail netting are taken from experimental data and represent the only biological information used by the simulation model.

The models described above vary in their capacity to answer the questions posed of them. Most are non-optimising predictive models and few employ detailed mechanistic models of fruit-tree growth that would enable the simulation of any orchard system from planting to maturity, hence the need to develop a more complex bioeconomic model of an apple orchard system.

3. Orchard management choices and practices

In the planting and management of an apple orchard a large number of choices and decisions concerning the most appropriate system face the grower. Barritt (1987) defines an orchard system as the integration of all the horticultural factors involved in establishing and maintaining a planting of fruit trees. Many decisions must be made before planting occurs, including choice of cultivar (variety), rootstock (tree size), tree density and pruning and training (tree form).

The apple cultivar determines fruit variety and fruit features such as size, shape, colour, flavour, firmness, ripening season and pest and disease resistance. The age at which an apple tree first bears fruit (its precocity) will vary according to the cultivar/rootstock combination.

A range of apple cultivars are normally grown in commercial apple orchards. A variety of reasons exist for choosing a particular cultivar: each type of apple may face distinct market situations and may potentially receive different prices; sequential harvest dates allow for more efficient picking and packing operations; some cultivars have a greater susceptibility to pests and diseases than others; and different cultivars may be necessary for pollination.

Tree size is central to an orchard system because of its economic implications. Trees that are large at maturity result in increased labour costs and often take many years to bear fruit. An objective of modern orchard design is to maintain smaller trees that are planted closer together. These smaller trees have the

additional advantage of earlier bearing habits. Tree size is most often controlled physiologically through rootstock selection.

Horticultural techniques used to manage vegetative growth and fruit production are pruning, training and thinning. While the level of thinning is determined each year, pruning and training are usually predetermined by choice of density, rootstock and cultivar when the orchard is established. These latter choices are made at planting and assumed to remain unchanged during the life of the orchard.

4. The model

Conceptual Biophysical Model

Apple tree growth during a growing season and over a lifetime is described using a carbon-balance model. Seasonal growth patterns that are peculiar to deciduous woody perennials such as apple trees, form an integral part of the model. The carbon-balance model is described in detail in Hester (2000) and only a brief overview is given here.

Figure 1 shows the conceptual biophysical model in diagrammatic form. The critical environmental variables in the model are daylength, temperature and light – all three affect the growth potential of the tree. Light (radiation) and daylength affect canopy photosynthesis, while temperature affects both photosynthesis and respiration. Light interception is critical to the amount of photosynthesis undertaken by an apple tree and level of interception is determined by shape of the tree which is, in turn, influenced by chosen pruning and training techniques and tree age. Net photosynthesis describes the amount of carbon available for tree growth after accounting for carbon lost during leaf respiration and gained through photosynthesis.

Carbon represents the energy used for growth by each tree component: roots; wood; fruit; and leaves. Respiration of these components results in energy losses. The 'fruit load' on the tree is the major determinant of how energy is

divided between each tree component and is influenced through a management practice known as thinning.

Fruit load also influences size of individual fruits and has an impact on future fruit production through its effect on amount of root, wood and leaf that grows in the current and following seasons. Fruit is harvested annually and its quantity and quality is taken into account by the model.

Apple trees follow temperature-driven patterns of growth and non-growth over a 12-month period. During late autumn, apple trees enter a dormant period where vegetative and reproductive buds require a period of chilling temperatures if bloom, growth and development are to occur in the spring. Dormancy is broken once the chilling requirement of the particular apple cultivar has been satisfied. Growth, however, does not automatically resume at this point, rather, it occurs following higher daily temperatures that result in accumulation of a certain number of heat units.

Bioeconomic Simulation Model

The economic model describes the costs and revenues associated with fruit production from an orchard system from planting to maturity. Annual fruit production is determined by the biophysical model and used in the economic model to simulate the annual profitability and net present value (NPV) of a particular system.

The relationship between the biophysical and economic models that make up the bioeconomic model is described in Figure 2. The yield and NPV of each orchard system will depend fundamentally on the variety, tree density and pruning/training regimes chosen when trees were planted. In addition, yield and profitability may be significantly modified each year through changing the amount of thinning undertaken, described by the decision variable $thin_t$. Thinning is used to modify the number of fruits a tree bears to maturity and thus it determines their size and influences the price they receive. The length of

the time horizon, T , also influences system NPV and can be included as a decision variable. The time horizon is important in assessing orchard rotation strategies, however, is not considered as a decision variable in the current model.

The decision variables can be viewed as being of two types. First, those pertaining to the establishment of the orchard and, second, to management decisions made annually. Thinning falls within the latter category.

Annual yield is used in the economic model to determine annual revenue from the system. Apple prices are assumed to be exogenous. The cost of establishing each orchard system as well as costs related to tree density and harvest are subtracted from revenue to determine overall profits for the particular system. Annual profits are discounted and summed over the life of the orchard to give NPV. In an optimising framework, decision variables are adjusted so that NPV is maximised.

Mathematical Model

The net present value (V) of the stream of annual profits obtained over the planning horizon $t=1, \dots, T$ is defined as:

$$V = \sum_{t=1}^T \pi_t(F_t(\mathbf{x}_t, \mathbf{u}_t)) \frac{1}{(1+r)^t} - CE \quad (1)$$

where the annual profit π_t is a function of fruit production per hectare F_t in year t , a state vector \mathbf{x}_t and a control vector \mathbf{u}_t ; r is the discount rate and CE is the cost of establishing the orchard starting with bare ground. Note that in the economic model time (t) is a discrete variable measured in years. Annual profit is described as:

$$\pi_t = (PF(w_F) - CF) \cdot F_t(\mathbf{x}_t, \mathbf{u}_t) - N \cdot CN_t(A_t) \quad (2)$$

where PF is the price of fruit (A\$/kg) and CF is the cost of harvesting the fruit (A\$/kg), N is the planting density (trees/ha), and CN_t represents costs per tree. Labour is the main component of harvesting cost (CF), and cost per kilogram harvested may depend on variety and orchard system used. Small, compact trees require less labour per kilogram harvested than large trees. However, the current rate per kilogram in Australia seems to be the same regardless of the orchard system and hence is used in the model. Density-related costs (CN_t) depend on age of the orchard (A_t) and consist of labour, materials, chemicals, fertiliser and other expenses, such as irrigation costs per tree, where:

$$CN'(A_t) > 0$$

$$CN''(A_t) \leq 0$$

These costs are also affected by the choice of orchard system which determines pruning and training requirements and ultimately affects the shape of the trees which, in turn, may have a bearing on time and effort required to apply chemicals, fertilisers and irrigation. In summary, all costs (CE , CF and CN_t) depend on the orchard system selected. The model represents a single orchard cycle starting with bare ground, thus $A_t=t$.

Annual fruit production from a particular system (kg/ha), determined by the biophysical model, is defined as:

$$F_t = N\sigma \int_{\tau=t}^{t+1} [(P_{d\tau} - R_{dF\tau})\psi + CHO\tau] \rho_{F\tau}(\mathbf{x}_t, \mathbf{u}_t) d\tau \quad (3)$$

where P_d is daily photosynthesis, R_{dF} is the daily respiration of the fruit, ψ is a conversion factor between carbon and dry matter (DM), CHO represents carbohydrate reserves and τ represents time measured in days. Thus the integral is fruit production per tree in the interval from the beginning to the end of year t . The integrand represents the daily amount of carbon partitioned to fruit production and growth, estimated as the proportion (ρ) which is allocated to

fruit on a daily basis. Note that the partitioning parameter, ρ_F , depends on state and control variables and these relationships are quite complex, as described in Hester (2000). The parameter σ converts carbon to fresh fruit weight.

The biophysical model consists of four state variables: leaf, fruit, wood and root. Each of these variables is associated with a differential equation for daily gain in mass of each component, that is numerically integrated on a daily basis in the simulation. From the standpoint of the economic model, leaf and fruit are not treated as state variables since they follow an annual cycle that, for a given orchard system and climatic events, depends on the amount of carbohydrate reserves available in wood and root at the beginning of the season. Thus, the state variable vector for each year is defined as:

$$\mathbf{x}_t = [R_t, W_t, D_t] \quad (4)$$

The state of an individual tree at the beginning of year t is described using dry matter content in root (R) and wood (W) and the presence of pests and diseases (D).

The control vector \mathbf{u}_t depends on the type of problem under study and may contain variables such as thinning and orchard time horizon. In this case, thinning is the only control variable, with a unique optimal value of thinning obtained for each year. The immediate objective of thinning in each year is to allow individual fruits to grow to the size that maximises profitability. Thus, the control variable vector is defined as:

$$\begin{aligned} \mathbf{u}_t &= [thin_t] \\ 0 &\leq thin_t \leq 1 \end{aligned} \quad (5)$$

Thinning takes on a value between zero and one, with values of zero indicating fruit is thinned so that no fruits remain on the tree, a level of one indicating all fruits remain on the tree and values between zero and one indicating proportional levels of removal. Thinning, ie. removing some fruit from a tree, is

one of the few ways an orchard manager may influence profitability of the apple crop. By removing some fruits at bloom or shortly afterwards, the size of the remaining fruits at harvest and their value is likely to be increased.

Biennial bearing and fruit size

The annual objective of thinning, to achieve the most profitable fruit size, is tempered by the effect of current fruit load on potential fruit size and yield in future years. If a tree bearing a large number of apples is thinned only lightly, it is probable that the tree will only be able to support a small number of apples in the following year which may negatively impact on profits. This tendency towards biennial bearing is inherent in many apple cultivars and may be modified by thinning. The orchard manager must therefore take into account both immediate and long-term fruiting prospects of the tree when determining the appropriate level of annual thinning to maximise NPV.

From a financial perspective, the effect of thinning on average fruit weight and consequently on the commercial value of yield is important. Following picking, apples are graded and packed into various ‘count’ sizes that are based on individual fruit weight and reflect number of fruit per carton. The value of the apple harvest is closely related to fruit size. Generally a crop of small apples is worth less than the same weight of larger apples, hence the incentive to improve fruit size through thinning.

Assuming that all apple cultivars are prone to biennial bearing, a biennial bearing pattern is imposed on fruit growth that sees a large crop followed by a light crop. Data on natural fruit bearing patterns is scarce although the biennial bearing pattern simulated by the biophysical model does compare reasonably with the fruit mass data from an Australian trial (Middleton, 1984; Middleton, unpublished data). The biennial bearing pattern is simulated as follows:

$$EFL_t = (BFL - (F_{L,t-1} - BFL)) \quad (6)$$

where EFL_t is expected fruit load when no thinning takes place, BFL is fruit load that would lead to minimal or no biennial bearing and F_{Lt-1} is fruit load in the previous year. The value of EFL_t depends on the amount by which actual fruit load exceeded BFL in the previous year. It is likely that the value of BFL varies with cultivar, rootstock and tree age, although these effects are ignored in the present study due to lack of experimental data and a single estimate is used. The estimate of BFL is set at a level that appears reasonable to the author given data from an Australian trial (Middleton, 1984; Middleton, unpublished data).

The process of thinning leaves a proportion of the original amount of fruit on the tree. The actual fruit load that results from thinning (F_{Lt}), is calculated as:

$$F_{Lt} = EFL_t \cdot thin_t \quad 0 \leq thin_t \leq 1 \quad (7)$$

Once F_{Lt} is determined, fruit number (FN) is calculated according to:

$$FN_t = F_{Lt} \cdot LA_{max_t} \quad (8)$$

where LA_{max_t} is the maximum leaf area, calculated from the biophysical model (see Hester 2000). Finally, average fruit weight (FW_t) is calculated as:

$$FW_t = \frac{Y_{Ft}}{FN_t} \quad (9)$$

where Y_{Ft} is the yield per tree measured in grams of fresh weight, calculated in the biophysical model. Average fruit weight is used in the economic model to determine the profitability of a given thinning strategy.

Price Data

In the bioeconomic model, prices received by the apple orchardist are assumed to be determined exogenously. For a given variety, apple prices vary according to individual fruit size. Apple size is approximated by the fruit ‘count’ or number of apples in an 18-kilogram carton. The higher the count, the smaller

the apple size (weight) and vice versa. Larger sizes receive a price premium; however, enormous apples receive a price penalty.

Data on prices received for each grade of apple variety are not regularly recorded at fruit selling centres in Australia, rather, only maximum, minimum and average prices for a variety are publicly available. Unfortunately the relationship between these prices and fruit size is not recorded. Detailed price by grade data was obtained for Granny Smith apples, sold during January 1999 and was used to estimate the grade price differentials associated with fruit size for all varieties. The relatively high prices for all count sizes reflect the shortage of Granny Smith apples on the market during January 1999.

For simplicity, it is assumed that the relative price differences shown in Table 2 hold regardless of maximum price. The data were used to estimate the following price-count relationships used in the economic model:

$$P_i \begin{cases} P_{75} & \text{if } count_i \leq 75 \\ \text{max price} & \text{if } 75 < count_i < 105 \\ -0.2448 \cdot count & \text{if } count \geq 105 \end{cases} \quad (10)$$

where P_{75} is the price for counts less than 75, *max price* is the price received for counts between 75 and 105 and c is the intercept term. Using the Batlow data P_{75} has a value of A\$36 per carton, max price is A\$43 per carton and c is 61.29.

5 Model Implementation

In this section, the profitability of one hectare of ‘Granny Smith’ apple trees is simulated over a planning horizon of 15 years from planting. The trees are planted on the semi-dwarfing MM.106 rootstock, at a density of 1000 trees per hectare and trained to the central leader system. The specific system chosen for simulation is one of those outlined in Hester (2000).

Detailed information on the price and quantity of labour, capital, chemicals, fertiliser, nutrients and irrigation for a range of orchard systems over a 15 year lifespan can be found in Hester (2000). All labour in the one-hectare orchard is priced at the casual rate of A\$11.11 per hour.

Costs related to tree density (CN) are presented in Figure 3 and are specific to the chosen system. Labour costs peak in year four after planting when pruning and training requirements are highest. After this time, labour requirements remain stable. Chemical and nutrient costs are lowest during the years immediately after planting but increase as the tree reaches maturity. The peaks in nutrient costs represent the cycle of applications that is adopted in this orchard. Capital costs for training are minimal in the central leader system and are incurred in the two years immediately after planting.

Establishment costs are estimated to be A\$8,770 per hectare for this orchard system, assuming a cost of A\$6.25 per tree purchased from a commercial nursery. Hester (2000) details parameter values that are specific to the simulation and values of non-system specific parameters.

The biophysical model, described by equation (3) is solved using numerical integration at daily steps and is implemented using the specialised simulation packages Simulink® and Matlab® (Mathworks 1996a, 1997). The biophysical model is solved for specific values of thinning and the resulting fruit quantities and sizes are used in the economic model to calculate annual profit and NPV.

6. Results and discussion

The effect of Thinning

Before optimisation took place, the effect of thinning was investigated in more detail. Simulated trees were thinned so that various amounts of fruit remained on the tree, and the effects of a given thinning rate, held constant over 15 years, were investigated. As thinning rates were varied for each 15-year cycle, their

effect on fruit weight, yield, price and per hectare NPV were analysed. Results of this analysis are shown in Figure 4.

Average fruit weight decreases in a non-linear fashion (Figure 4 A) as a greater number of fruit is retained on the tree (thinning level increases). This relationship reflects the competition between individual fruits for the given amount of energy available for fruit growth. Although available energy for fruit growth increases as the fruit load on the tree increases, this additional energy does not compensate for the increased demands of a greater number of fruit, hence the decrease in average fruit weight.

The decrease in average fruit weight has implications for the average price received for the fruit (Figure 4 B). When fruit is thinned so that only a small number of fruits remain on the tree ($thin = 0.05$) average price is slightly above A\$2.00 per kilogram. At this level of thinning average fruit weight, and hence size, is greatest. Highest prices are not received here because the largest sized apples (count >75) do not receive the highest price per kilogram. Fruit price does increase as more fruit are left on the tree and a drop in average weight (size) improves their value. Apples receive the highest price per kilogram when thinning leaves between 20 and 25 per cent of fruit on the tree ($0.2 \leq thin \leq 0.25$). Beyond this level of thinning average fruit price decreases in line with reductions in fruit size that put the fruit in lower-valued count sizes.

While leaving progressively more fruit on the tree does reduce average fruit weight, it also has the effect of increasing total fruit weight on the tree, or yield (Figure 4 C). As thinning increases, yield per tree also increases, but at a decreasing rate. When thinning leaves only around five per cent of fruit on each tree ($thin = 0.05$), total yield is approximately 20 kilograms per tree, and increases to around 75 kilograms of fruit per tree when thinning leaves around 55 per cent of fruit on the tree ($thin = 0.55$). However, at high yields, average fruit size is small and average price per kilogram of fruit is well below the maximum.

Ultimately, the value of thinning hinges on its effect on NPV. As thinning values increase from 0.05 to 0.45, NPV increases (Figure 4 D) to a maximum and decreases thereafter. Prior to the level of thinning that produces maximum NPV ($thin = 0.45$), the increased yield per tree appears to have compensated for the reduced price per kilogram received for the progressively smaller fruit. However, beyond a thinning level of 0.45 average fruit size is reduced to a level that receives dramatically lower prices, and the increase in average yields per tree does not compensate for this price drop.

It is interesting to note, therefore, that maximum NPV does not occur where prices are at a maximum. Nor does it occur where fruit yield or fruit weight are at a maximum. Rather, the strong trade off between total yield per tree and individual fruit weight results in the achievement of maximum NPV where prices are below the maximum level.

This simple analysis provides insight into the operation of the model and the effect of thinning. However, these results only apply when thinning is treated as a static variable, taking the same value every year.

Dynamic Optimisation results

Various solution techniques are available to optimise the dynamic bioeconomic model: dynamic programming; non-linear programming (NLP); and genetic algorithms (GA). While the model was optimised using both GA and NLP procedures in Hester (2000), only the results of the GA solution technique are presented in this paper. Additional details of the GA solution technique can be found in Cacho (1998) and Cacho and Simmons (1999).

The optimal thinning trajectory obtained by the optimisation routine is given in Figure 5. This trajectory gives a cumulative fruit yield of 967 kg/tree over the 15 year period with an NPV of A\$1,265,000 over the same time horizon.

Fruit number per tree, average fruit weight, price per kilogram and the discounted value of profit that result from the optimal thinning trajectory are given in Figure 6.

Average fruit yield per tree (6.A) rises consistently over time, although the increases in years 2 to 4 are slower reflecting the thinning regime during this time when relatively large amounts of fruit were left on the tree. Average fruit weight remains constant after year four (6.B) and maximum prices per kg are received in all but the second year from planting (6.C). Annual discounted profits are affected by fruit prices resulting from the optimal thinning strategy (6.D). Before the trees begin to bear fruit, initial establishment costs and variable costs result in a negative profit. Profit continues to rise until year 10 when it levels out and remains reasonably constant for the remainder of the time period.

Yield results over 15 years are compared with a situation of no thinning in Figure 7. Trees are deblossomed until the tree has grown to a size where fruit bearing is considered feasible. This is determined according to the measurement of the trunk cross-sectional area and, in this case, the first year of bearing is year two following planting, for both thinning and no thinning strategies. When no thinning takes place, the biennial bearing pattern that results from the model shows a very clear and consistent pattern of alternation between the 'off' year and the 'on' year of fruit production. In the 'on' years, yield increases from 18 kg per tree in year two to around 200 kg per tree in year 14. In the 'off' years, no fruit is produced due to the effect on the tree of the high yields in the previous year. This contrasts with fruit production per tree using the optimal thinning strategy, where the cycle of dramatic fluctuation is eliminated.

The fruit load on a tree is adjusted by thinning. The path of fruit load adjustment that results from optimal and no thinning is shown in Figure 8. When no thinning occurs, the 'on' years produce a fruit load of 20 fruits per m² of leaf area, and a fruit load of zero in the following year. The optimal thinning

strategy modifies these dramatic fluctuations and fruit load appears to settle at a value of six fruits per m² of leaf area. Small fluctuations occur in the earlier years but are reduced to almost no variation by year ten.

7. Summary and Conclusion

The lack of a suitable model to analyse a range of production issues confronting an apple orchard manager led to the development of a complex bioeconomic model discussed in this paper. The model allows simulation of the effect of management decisions on any apple orchard system from planting to maturity. The simulation discussed in this paper focusses on optimal thinning rates over the lifetime of the orchard given an inherent tendency towards biennial bearing of many apple tree cultivars.

Before optimisation occurred, thinning was investigated in a non-optimising framework where its value remained static in each year of the 15-year planning horizon. As thinning rates were varied for each 15-year cycle, its effect on fruit weight, yield, price and per hectare NPV were analysed. It is interesting to note that, when treating thinning as a static decision variable, maximum NPV did not occur where prices were at a maximum. Nor did it occur where fruit yield or fruit weight were at a maximum. Rather, the strong trade off between total yield per tree and individual fruit weight resulted in the achievement of maximum NPV where prices were below the maximum level.

Using the genetic algorithm solution technique, the model was optimised to provide the level of thinning in each year that maximised NPV. After initially fluctuating, presumably to null the effect of the tendency towards biennial bearing, the optimal level of thinning remained reasonably constant from year 5 to 15. Yield per tree gradually increased as did the discounted value of profit. In all but one year, the optimal thinning strategy resulted in fruit growing to a size that received the maximum price per kilogram.

Incorporating the biennial bearing habit into the model and optimising decisions that influence it, represents a significant contribution to understanding the apple orchard problem. Additional uses of this model, detailed in Hester (2000) include simulating lifetime system profitability given details of system parameters and simulation of the reduction in profit caused by a pest outbreak.

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