5. Data and Assumptions

In this chapter data requirements for orchard profitability simulations are described. Each orchard system, made up of particular combinations of cultivar, rootstock, density, training and pruning strategies, has varied implications for orchard profitability through differences in production costs, yield and prices. Production costs for a selection of orchard systems that will be used in applications of the bioeconomic model are described in this chapter. The literature is reviewed for information on labour, capital and other orchard costs and is used as a guide to determining costs that are appropriate for each system. Details of price determination are also given in this chapter.

5.1 Orchard Systems

Given the large number of cultivars, rootstocks and training systems available in orchard design, an extremely large number of orchard systems are possible and it would be difficult to simulate each one. In addition, lack of time-series data on production costs and yields means accurate modelling of a large portion of possible systems would be difficult.

A range of orchard systems is selected for consideration and these systems are described in Table 5.1. Four rootstocks are chosen, ranging from the very dwarfing M.9 and M.26 rootstocks to the semi-dwarfing rootstocks MM.104, MM.106 and the vigorous Northern Spy rootstock. Cultivars grown on these rootstocks will grow to a range of sizes as suggested by each rootstock/density combination and trees planted on the very-dwarfing rootstocks will reach maximum production earlier.

The final tree size implied by rootstock choice makes each rootstock more suitable to particular tree densities and training systems than other rootstocks. The M.9 rootstock is suited to very intense density and input systems of 2000 trees per hectare and above as the smaller size of trees allows them to be planted closer together. The chosen densities for this rootstock are 4400 and 2666 trees per hectare. Since M.26 is not quite as dwarfing as M.9, trees on M.26 reach a slightly larger size at full production. A density of 1666 trees per hectare is chosen for this rootstock. Systems on M.9 and M.26 are classified as high density and high input systems. Systems containing the MM.104 and MM.106 rootstocks have densities of 800 and 1000 trees per hectare respectively, and are known as medium to high density input systems. Finally, Northern Spy rootstock produces the largest trees of all the chosen systems, at a density of 280 trees per hectare.

Table 5.1: Orchard systems used in this study

System	Hi-Early Delicious, Gala	Granny Smith, Fuji, Pink Lady
M.9		
Density (trees/ha)	2666	4400
Spacing between trees X row (m)	1 X 3.75	0.5 X 1.0 X 4.0
Training systems	Slender spindle	V trellis
Support	Yes	Yes
T_f	0.3	0.59
	Hi-Early Red Delicious, Gala, Granny Smith, Fuji, Pink Lady	
M.26		
Density (trees/ha)	1666	
Spacing between trees X row (m)	1.5 X 4	
Training system	Central leader	
Support	Yes	
T_f	0.37	
MM.104		
Density (trees/ha)	800	
Spacing between trees X row (m)	2.5 X 5	
Training system	Central leader	
Support	Yes	
T_f	0.35	
MM.106		
Density (trees/ha)	1000	
Spacing between trees X row (m)	2 X 5	
Training system	Central leader	
Support	No	
T_f	0.31	
Northern Spy		
Density (trees/ha)	280	
Spacing between trees X row (m)	6 X 6	
Training system	Vase	
Support	No	
T_f	0.52	

The chosen training systems include V-trellis and slender spindle for trees grown on M.9 rootstocks, central leader for those trees growing on M.26, MM.104 and MM.106 rootstocks with trees growing on Northern Spy trained to the traditional vase shape.

The cultivars chosen for modelling within the systems are largely varieties that are gaining in popularity in Australian orchards: Fuji, Gala, Hi-Early Red Delicious and Pink Lady, with Granny Smith representing the only traditional variety. While some differences in growth rates, or vigour, occur between these cultivars, these differences are largely ignored. In this study, vigour differences are only considered when cultivars are planted on M.9 rootstocks. Because Hi-Early Delicious and Gala are slightly less vigorous than Granny Smith, Fuji and Pink Lady, the former group are planted in higher densities on M.9 (Table 5.1). In the design of the systems it is assumed that soil type, which influences tree growth, is classed as medium vigour (Fleming, 1996).

5.2 Labour Requirements

Labour is a necessary and costly part of orchard operation. While the specific cost of labour used per hectare depends on the orchard system, Quamme et al. (1997) estimate labour costs amount to between 16 per cent and 19 per cent of gross orchard revenue.

In addition to general orchard maintenance, labour is used in the specific cultural practices of pruning, training, thinning and harvesting. Perry et al. (1997) investigated labour requirements for cultural practices in various one hectare orchard systems, at densities of at least 1000 trees per hectare. It was found that time spent harvesting accounts for between 50 per cent and 63 per cent of total labour time, thinning accounts for between 12 per cent and 26 per cent of labour time, with the remaining time attributable to pruning and training tasks, depending on the system.

While no comprehensive list of labour requirements for each orchard system is available, those that were located in the literature are listed in Tables A.1 and A.2 of Appendix A. Labour used in pruning and training are measured in terms of minutes per tree over a season or a number of seasons. Labour required for harvest is measured both in terms of minutes required to pick one kilogram of apples and total minutes required to pick all apples from a tree. Differences in labour requirements for cultural practices reflect tree size and height, tree age and tree form that results from each training strategy. Labour requirements for harvest and other cultural practices are expected to be higher when the chosen system results in tall trees that require the use of ladders.

Quamme et al. (1997) compare labour efficiency for five different training systems, and find that each has a significant impact on orchard productivity. Training systems that are commonly used in high density plantings, slender spindle and vertical axis, are compared with two more conventional systems, the central leader and the van Roochoudt trellis with two cultivars, 'Jonagold' and 'McIntosh', at various planting densities. Each system has varied labour requirements for pruning and training.

Results from Quamme et al. (1997) are reported in Tables A.1 and A.2. Over the life of the trial (nine years), trees trained as central leader on M.4 rootstocks had relatively high labour requirements per tree for pruning and training for both Jonagold and McIntosh cultivars (34.6 and 28.71 minutes). Other systems requiring large amounts of labour for pruning and training are Jonagold and McIntosh trained as slender spindle trees (28.66 and 34.96 minutes per tree). McIntosh trees trained to central leader on both M.4 and M.26 rootstocks also had high labour requirements for thinning relative to other systems. Harvest labour requirements over the nine years varied significantly between systems and were highest for central leader on M.4 rootstock (34.16 minutes per tree). When measured on a per kilogram basis there was little difference between harvest labour requirements for each system. The large amount of time required for cultural practices over nine years in various systems is reflective of the size of trees and necessary use of ladders in the work. Between six and ten per cent of all cultural practices were carried out from a ladder over the nine-year trial. Trees trained as slender spindles required no work with ladders. The systems with the highest requirement for ladder work (ten per cent) were McIntosh trained to central leader and both cultivars trained as vertical axis.

When considering total harvest requirements on a per tree basis, Jotic and Oakford (1989) also found significant differences between tree systems (data not shown). The systems containing trees trained to Lincoln Trellis made the highest demands on harvest labour over the four-year trial (30.12 and 46.65 minutes per tree). However, as was the case with Quamme et al (1997), when measured on a per kilogram basis, there was little difference in labour demands between each system (0.24-0.34 minutes/kilogram).

Perry et al. (1997) investigated time (labour) required to prune, train, hand thin and harvest trees grown under various training systems: central leader; slender spindle and vertical axis. In the trial, the systems reached final heights of 4.2m, 2.5m and 3.8 m respectively. Data on labour use in the trial are reported in Table A.2 of Appendix A in terms of total labour efficiency, that is, the amount of labour used in all cultural practices per kilogram of fruit produced. Lower values equate to higher labour efficiency, or less labour hours needed to produce fruit. The authors found that slender spindle trees required most labour per kilogram of fruit, requiring 3.6 minutes and 3.34 minutes to grow one kilogram of 'Empire' and Jonagold fruit respectively (Table A.2). Trees trained as central leaders were least labour intensive, followed by those trained to vertical axis. Specifically, central leader and vertical axis trees required more time to harvest while slender spindles required more labour in the training and pruning process. Systems containing the Empire cultivar required greater labour time in the thinning processes (data not shown).

In a study by Clayton-Greene (1989a), labour requirements of various training systems for a single cultivar/rootstock combination are compared for the fifth year of production. The study showed only slight differences in harvest labour requirements for each training system when measured on a per kilogram basis. Marked differences did occur in the time taken to prune the trees. In all the systems where a significant amount of trellising is involved there were high labour demands, ranging from 4.6 minutes per tree for the Italian palmette to 9.72 minutes per tree for the Ebro-espalier system. This compares with labour requirements for 1.51 minutes per tree for the minimal pruning/French axis system, to 4.19 minute per tree for the central leader system.

The time required to pick one kilogram of apples decreased with increasing tree density according to Goedegebure (1989). Labour required to pick one kilogram of apples from trees planted at 1125 trees per hectare, at full production and trained to slender spindle, was 0.43 minutes. It took slightly less time to pick a kilogram of apples from trees planted at a density of 4500 per hectare (Table A.2), because the system contained relatively smaller trees. While fruit may be picked more quickly at higher densities, the large number of trees in high density plantings result in higher total labour requirements for harvesting each hectare.

As apple trees grow, time spent on cultural practices changes. Clayton-Greene (1989b) investigates orchard costs from planting to maturity and records the change in labour requirements. For trees trained to central leader it was found that pruning and training requirements for labour are greatest in the years immediately following planting and minimal from year six onwards (Table A.2). During the early years time is spent achieving desired tree form as quickly as possible. The trees trained to Tatura trellis also follow this trend. However, this style of training is more expensive in terms of labour time. Labour requirements range from 9.9 minutes per tree in year two to 4.52 minutes per tree from year six onwards. This compares to labour requirements of 4.94 in year two, to 1.77 minutes per tree from year six onwards for central leader training and pruning.

Tables A.1 and A.2 give details of labour requirements for particular orchard systems that are available in the literature. Unfortunately, the list is not comprehensive. Since information on labour requirements from the literature does not cover all systems selected for analysis in this study (Table 5.1), data from tables A.1 and A.2 were used as a guide in estimation of labour costs over time for selected systems. Additional assumptions used in estimation of labour requirements for systems contained in Table 5.1 are:

- per-tree labour requirements for training of trellised systems are two to three times the input required for free standing trees (Clayton-Greene, 1989a);

- labour requirements for spray labour: 0.22 minutes per tree;

- labour required for training in medium density systems (300 to 1000 trees per hectare) and high density systems (1000 to 1500 trees per hectare) is high in years two and five after planting and subsequently decreases to a constant requirement from year six onwards;

- labour required for training in very high density plantings is high in year two after planting, it drops in year three and increases in the following years until maturity; and

- for a given training system, higher tree densities require less labour time for pruning than trees in less densely planted systems due to the smaller size of the former.

Using these assumptions, and experimental results from the literature, labour requirements for pruning and training of the orchard systems listed in Table 5.1 were obtained. Labour times required for planting, pruning and training are given in Table 5.2 while estimates of labour required for thinning are given in Table 5.3. Data in italics have been estimated due to a lack of experimental data while other data were taken directly from the literature. All data on labour requirements for thinning have been estimated due to lack of experimental data.

When modelling labour requirements of particular orchard systems, provision of labour is also an important issue. For some orchard systems it may be possible that the owner's labour is sufficient to undertake all cultural practices while in others it is necessary to hire labour for all tasks with owner labour used in general orchard maintenance work. The need to hire additional labour depends on the size of the orchard and therefore on the magnitude of pruning, training, thinning and harvesting tasks. While timing of pruning, training and thinning is an important part of orchard profitability, there is a degree of flexibility in timing that has implications for labour hiring. In contrast, there is little or no flexibility in harvesting. Each variety of apples is picked at a particular level of maturity. In developing long-term cost estimates for orchard establishment and maintenance it is assumed that all cultural practices (pruning, training, thinning and harvesting) are undertaken using casual labour.

Table 5.2: Labour requirements (minutes per tree) for planting, pruning and training of apple cultivars in the orchard systems modelled

		Age (years after planting)													
Density	**Planting year**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Vase															
280	3.60	*0.85*	*1.70*	*2.55*	*3.40*	4.92	*5.90*	*6.89*	*7.88*	*8.86*	*9.85*	*10.80*	*11.80*	*12.80*	*13.80*
Central Leader															
800	3.60	4.94	3.25	3.11	5.68	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77
1000	*3.60*	*5.00*	*3.50*	*3.25*	4.19	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*	*2.00*
1666	5.67	0.27	1.62	0.69	1.41	1.86	1.98	*2.73*	*2.73*	*2.73*	*2.73*	*2.73*	*2.73*	*2.73*	*2.73*
Slender Spindle															
2666	4.64	0.22	1.94	0.62	1.12	1.52	1.54	2.04	2.04	2.04	2.04	2.04	2.04	2.04	2.04
V-Trellis															
4400	4.12	0.18	2.12	0.58	1.00	1.30	1.30	1.70	1.70	1.70	1.70	1.70	1.70	1.70	1.70

Note: numbers in italics indicate time for the task has been estimated

Table 5.3: Labour requirements (minutes per tree) for thinning of apple cultivars in the orchard systems modelled

	Age (years after planting)														
Density	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Vase															
280	*0*	*0.6*	*0.8*	*1.1*	*1.6*	*3.0*	*3.4*	*3.9*	*4.4*	*6.6*	*7.3*	*7.9*	*8.6*	*9.2*	*9.9*
Central Leader															
800	*0*	*0.6*	*1.0*	*1.5*	*1.8*	*2.0*	*2.5*	*2.5*	*3.0*	*3.0*	*3.0*	*3.0*	*3.0*	*3.0*	*3.0*
1000	*0*	*0.6*	*1.0*	*1.5*	*1.8*	*2.0*	*2.3*	*2.3*	*2.3*	*2.3*	*2.3*	*2.3*	*2.3*	*2.3*	*2.3*
1666	*0*	*0.6*	*1.0*	*1.3*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*	*1.5*
Slender Spindle															
2666	*0*	*0.6*	*1.0*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*	*1.3*
V-Trellis															
4400	*0*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*

Note: numbers in italics indicate time for the task has been estimated

5.3 Capital

Capital required by the orchard operation can be divided into items that are related to the type of orchard system and those that are required regardless of orchard system. The latter consist of tractors, spray equipment and other machinery, storage sheds and irrigation pumps. Since these items are required regardless of the orchard system they are not considered in this study. Rather, only capital items that are system dependent are considered. System dependent capital items consist of materials required for trellising, tree support and training. This is consistent with general economic results that production equilibria reflect variable, not fixed, costs.

The level of system-dependent capital investment is driven by choice of rootstock since this largely determines appropriate training strategies for trees and whether support structures are necessary (Table 5.1). Cultivars on dwarfing and semi-dwarfing rootstocks, M.9 and M.26, regardless of training strategy, usually require some form of support because of weak anchorage. This support may come from a wooden post or a wire trellis. The boundary between those trees that need support and those that do not is not well defined because factors such as soil depth and fertility, environmental conditions and water, nutrient and pest/disease status may also influence the strength of tree growth (Somerville, 1996). Specific capital requirements for support structures, where they are needed, are listed in Table 5.4.

Central leader, slender spindle, V-trellis and vase are training systems considered in this study. Capital requirements range from very few in central leader type systems to very high requirements for trellis-type training systems. This is because central-leader training allows the tree to grow to its natural form whereas a particular form is imposed on trees trained in trellis systems.

Support in the central-leader system is only necessary when cultivars are grown on the M.26 rootstock. In this case support is provided by a wooden post every 20 metres, with three wires passing through each at regular intervals. Trees in the slender spindle system require one stake per tree, while trees on the V-trellis require significant capital investment in wooden posts, wire and cable. No support is necessary when trees are grown on the Northern Spy rootstock.

Table 5.4: Capital costs ($/hectare) assumed in the model

	Planting Year					Year One		Year Two		Total Capital Costs
	Post (3m x 125mm) (no/row) [a]	Stakes (3m x 75mm) (no/tree)	cost ($/unit) [a]	Length of wire per row (m)	cost wire 2.65mm x 1km ($/row) [b]	200mm trainers (no/tree)	Cost 200mm trainers ($/unit) [c]	400mm trainers (no/tree)	Cost 400mm trainers ($/unit) [c]	Cost /ha
Central Leader										
800 tr/ha	–	–	–		–	4	0.40	4	0.60	3,200
1000 tr/ha	–	–	–		–	4	0.40	4	0.60	4,000
1666 tr/ha (69 rows)	6	–	19.90	360	27.90					10464 [d e]
Slender Spindle										
2666 tr/ha	–	1	9.00			–	–	–	–	23,994
V-Trellis										
4400 tr/ha	–	–	–		–	–	–	–	–	10,000

a Source: Tamworth Treated Timbers, Kootingal, NSW
b Source: Seed and Grain Sales, Armidale, NSW
c Source: Leigh Durham, Horticultural Consultant, Bacchus Marsh, Victoria, Australia
d Source: Middleton, S.G. pers. comm.
e Includes labour input

The systems vary in their requirements for capital items that are additional to support structures. No training aids are used when trees are pruned to the traditional vase shape. Only cultivars trained to central leader on MM.104 and MM.106 require limb spreaders to maintain branches at broad angles away from the central trunk (leader).

Estimates of capital requirements and training aids are reported in Table 5.4. Capital costs of trellising, support posts and wires are incurred in the year of planting, while cost of spreaders used in central leader systems are incurred as trees grow. Rather than itemise the costs of the V-trellis system, the total cost of its erection per hectare is given.

5.4 Chemicals

Most orchardists consider use of chemicals a necessary and important part of commercial apple production. These apple growers apply many chemical sprays to orchards each season, aiming to protect the apple trees and their fruit against damage from pests and diseases. Most chemicals have specific functions: herbicides are sprayed on the ground under trees to control weeds; fungicides control fungal diseases; insecticides are used for insect control; and miticides are used to control mite pests.

A list of common pests and diseases found in Eastern State apple orchards and chemicals used in their treatment is given in Table 5.5. The table was developed using information from Gordon and Walker (1991), Thwaite et al. (1998), QDPIE (various) and Mabbott R.J. (pers. comm.). The chemical name, registered trade name and application rates per 100 litres of water are derived from Thwaite et al. (1998). While only one trade-named product is proposed as a treatment for each pest, a range of different products are available for eradication of most pests. The products listed were selected for use in estimating chemical costs in the simulation model.

The necessary number of applications of a particular chemical during a growing season varies according to climatic conditions, both seasonally within one location, and between locations. The number of possible application rates is listed in column 5 of Table 5.5 and the number of applications assumed by the simulation model is listed in column 6. Chemical costs used in calculation of the cost per 100 litres were obtained from Seed and Grain Sales, Armidale, NSW during May 1999. The prices are reported in Table 5.6.

Table 5.5: Calendar of chemical use to treat pest and disease outbreaks

Disease/pest treated	Chemical	Registered Trade name	Rate per 100 L	No. annual applications	No. annual applications assumed in model	Cost per 100L
	Insecticide					
Codling moth	Azinphos Methyl	Benthion 350®	140 ml of 350 g/L liquid	5-11	7	3.01
Apple dimpling bug	Endosulphan	Endosan®	190 ml of 350 g/L liquid	2-3	2	1.47
San Jose scale	Petroleum spray oil	Winter oil	2 L	1	1	3.5
Woolly aphid	Vamidothian	Kilval®	0.125 L	1 every 2 years	1 every 2 years	4.30
	Fungicides					
Apple scab	Copper oxychloride	Copper	500 g	1	1	1.08
Apple scab	Dodine	Melprex®	80 ml of 320 g/L liquid	6-9	8	1.32
Powdery mildew	Penconazole	Topas®	25 ml of 100 g/L liquid	3-4	3	2.24
	Miticides					
mites	Tebufenpyrad	Pyranica®	25 g of 200 kg w.p.	1	1	5.12
mites	Propargite	Omite®	100 g of 300 g/kg w. p	1 if reinfestation	0	2.80
	Herbicides					
Annual/perennial weeds	Paraquat/diaquat	Sprayseed®	2.8 L of liquid[b]	3-6 (before age 3)	4	16.88[a]
Annual/perennial weeds	Glyphosate	Roundup®	2.5 L of 360 g/L liquid[b]	3-4 (3 years +)	3	24.92[a]

[a] Cost per hectare

[b] Rate per hectare

Table 5.6: Prices of chemicals used in cost calculations

Chemical name	Registered trade name	Unit	Price/unit ($)
Insecticide			
Azinphos methyl	Benthion 350®	10 L	215
Endosulphan	Endosan 350®	20 L	155
Petroleum spray oil	Winter oil	20 L	35
Vamidothian	Kilval®	5 L	172
Fungicides			
Copper oxychloride	Copper oxychloride	25 kg	54
Dodine	Melprex®	20 L	330
Penconazole	Topas®	5 L	449
Miticides			
Tebufenpyrad	Pyranica®	1 kg	205
Propargite	Omite®	10 kg	280
Herbicides			
Paraquat/diaquat	Sprayseed ® (135P/115D)	20 L	178
Glyphosate	Roundup 360®	20 L	135

Resistance to chemicals is a serious problem in Australian apple orchards and occurs when the chemical no longer provides the control against a pest that it did previously. Resistance by mites to many known miticides is a particularly serious problem. To avoid the development of resistance to miticides no product containing a particular chemical type is used more than once during a season.

Additional assumptions used in the development of annual spray schedules over the lifetime of the orchard are as follows:

- No resistance of mite or other pests to the chemicals used to eradicate them is present in the orchard; however, strict adherence to resistance management principles in the use of miticides and other pesticides occurs.

- The spray quantities applied to each hectare vary slightly as the apple trees grow. For blocks of one-year-old trees, the application rate is 500 L/ha, two-year-old trees are sprayed at a rate of 1000 L/ha, three-year-old trees at a rate of 1200 L/ha and all other aged trees at a rate of 2000 L/ha.

5.5 Fertiliser and Nutrients

Application of fertiliser and nutrients during and following planting is an essential part of commercial apple orchard operation. The application of nutrients is different for bearing and non-bearing trees. A normal pattern of fertiliser application used in Eastern States orchards is given in Table 5.7 The table was developed using information from Gordon and Walker (1991), Thwaite et al. (1998), QDPIE (various brochures) and Mabbott, R.J. (pers. comm.). Varied rates of urea and potash are applied annually depending on the fruiting status of the tree. Calcium nitrate is applied to trees from year three and may be applied as either a foliar spray or through the irrigation system. Dolomite, zinc sulphate and boron are applied every second or third year. Prices for nutrients were obtained from Seed and Grain Sales, Armidale, NSW and are listed in Table 5.8.

Table 5.7: Calendar of fertilisers and nutrients applied to apple trees

Nutrient	Comment	Application rate	No. annual applications	Cost per tree
Urea	Non-bearing	110 grams/tree	1	0.05
Urea	Bearing	550 grams/tree	1	0.23
Muriate of Potash	Non-bearing	50 grams/tree	1	0.02
Muriate of Potash	Bearing	250 grams/tree	1	0.90
Calcium Nitrate	Starts year 3	0.8 kg /100 litres	2–6	0.58[b]
Dolomite	1 year in 3	3 tonnes/hectare	1	488.00[a]
Zinc sulphate	1 year in 2	2.5 kg/100 litres	1	2.95[b]
Boron	1 year in 2	0.28 kg/100 litres	1	0.92[b]

[a] per 1000 trees
[b] Cost per 100 litres

Table 5.8: Prices of nutrients used in cost calculations

Nutrient	Trade Name	Unit	Price/unit ($)
Nitrogen	Urea	50 kg	16.90
Potassium	Muriate of Potash	50 kg	18.75
Calcium	Calcium Nitrate	25 kg	18.00
Calcium	Dolomite	41.8 kg	6.80
Zinc	Zinc sulphate	25 kg	29.50
Boron	Solubor	25 kg	84.00

5.6 Irrigation

Irrigation becomes necessary during the growing season at times of deficit rainfall. Irrigation requirements are likely to vary between orchard location and tree density. Seasonal water requirements per tree are listed in Table 5.9. Water requirements for trees planted at densities below 1666 trees per hectare are taken from Sevil and Smith (1997) and apply to growers in the Granite Belt of Southern Queensland, Australia. It is assumed that smaller trees planted at densities of 2666 to 4400 trees per hectare require reduced amounts of water. Water requirements for these trees is estimated in Table 5.9.

The costs of irrigation materials and pumping costs used in the simulation are given in Table 5.10. The purchase of an irrigation pump is not included in this study although it is assumed that a pump powered by a diesel engine is used, and that pumping capacity is 340 litres per hour per 100 metres. While the pumping rate is assumed not to vary as the area irrigated increases, a progressively larger pump would normally be required.

Table 5.9: Water requirements (litres per tree) assumed by the model

	Year 1	Year 2	Year 3	Year 4	Year 5 +
Density (trees per hectare)					
280 to 1666[a]	400	800	1200	1600	2000
2666	*200*	*400*	*600*	*800*	*1000*
4400	*100*	*200*	*300*	*400*	*500*

[a] Source: Sevil and Smith (1997)
Note: italics represent estimated water requirements

Table 5.10: Variable Irrigation costs used in the model

	Unit	Cost/unit ($)	Source
Taps (Valve)	100m	7	Southern Cross Irrigation, Tamworth, NSW
Dripper tape	100m	40	Southern Cross Irrigation, Tamworth, NSW
Diesel	litre	0.67	Average price, May 1999

In order to calculate the amount of fuel used in orchard irrigation it is assumed that the pump has a capacity of one horsepower when the irrigation of only one hectare of orchard is under irrigation. The engine capacity required to irrigate five hectares of orchard is assumed to be six horsepower. The use of diesel is calculated at 0.704 litres per horsepower per hour (Southern Cross Irrigation, pers. comm.).

The variable irrigation costs incurred from installation of sub-mains and irrigation pipe are given in Table 5.10. It is assumed that all trees are irrigated using trickle tape, in rows of 100m with a ball valve at one end of each row. The cost of diesel, used to power the pump is assumed to be A$ 0.67, the prevailing price at the time of writing.

5.7 Price of Apples

Australian apples are sold in both domestic and export markets. Exported apples from Australia face competition for markets from many other apple exporting nations, including New Zealand, United States, Argentina, Chile, South Africa and China. All countries export a range of apple varieties and face increasing trade barriers to their apple exports on food safety grounds, especially from the European Union and United States markets. Additional destinations for apple exports are in Asia.

Quarantine issues continue to prevent other countries from exporting apples into Australia. Among the pests and diseases absent from Australian pome fruit orchards is fireblight (*Erwinia amylovora*) which is endemic in North America, Europe, parts of Asia and New Zealand. Quarantine laws also prevent apples from travelling freely within Australia. In particular, fruit and vegetables produced outside Western Australia are prevented from sale in that state. Many pests and diseases, including codling moth, which affect apple and pear trees, are absent in Western Australian orchards.

The Australian apple and pear industry contains approximately 2000 growers with an average of 34 hectares (AAPGA, 1996). Apple orchardists are usually price takers. While traditional varieties such as Granny Smith, Golden Delicious and Red Delicious still dominate Australian total apple production, the number of these trees being planted is declining. Tree numbers and production of new varieties including Fuji, Gala, Hi-Early Red Delicious, Pink Lady and Lady Williams are steadily increasing.

A large number of apple varieties are available to consumers and each possesses particular quality characteristics, including size, taste and colour traits. Differences in characteristics between varieties are reflected in a range of prices for a given sized fruit. Commonly, it is the new varieties, bred for specific taste and colour attributes, that attract higher prices relative to the more traditional varieties. In addition to price variation between apple varieties, a range of prices is paid for apples of different sizes within a variety, ranging from low prices for small fruits to higher prices for large fruits.

In addition to price variation caused by varietal and size differences, domestic market prices often vary seasonally. Each apple variety ripens at a different date depending on the orchard location and certain Eastern States producers are able to receive a price premium because a particular variety matures earlier in their region compared to other regions. This is often the case for producers at Stanthorpe, Queensland, where fresh season apples may reach the market several weeks before the same variety of apple from regions in the south. As ripening occurs in the more southern districts, supply increases and price premiums are reduced. The level of the price premium may be affected by the amount of apples produced in the previous season that remain to be sold.

Apples that are graded as unsuitable for sale in the first-grade market may be sold into the apple-juice market. Variety has no impact on price in this market, although prices per tonne of juice fruit may vary according to whether apples are red or green in colour. This market is not considered in this study.

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 one sale from the Batlow Fruit Co-operative Ltd. The price data is for Granny Smith apples, sold during January 1999 and was used to estimate the grade price differentials associated with fruit size for all varieties. Data supplied by Batlow Fruit Co-operative are presented in Table 5.11. The relatively high prices for all count sizes reflect the shortage of Granny Smith apples on the market during January 1999.

Table 5.11: Price data used to develop price-count relationship

Count	Price per 18 kg carton ($)
70	36
80	43
90	43
100	43
110	38
120	31
135	25
150	24
165	21
180	16
198	15

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

$$P_t \begin{cases} P_{75} & \text{if } count_t \leq 75 \\ max\ price & \text{if } 75 < count_t < 105 \\ -0.2448.count & \text{if } count \geq 105 \end{cases} \tag{5.1}$$

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.

Comparison of the actual count prices and those used by the model are given in Figure 5.1. It is important to note that the largest apples (count <75) do not receive the highest price. It is assumed that the relativities are maintained as the maximum price changes, hence the price line moves vertically.

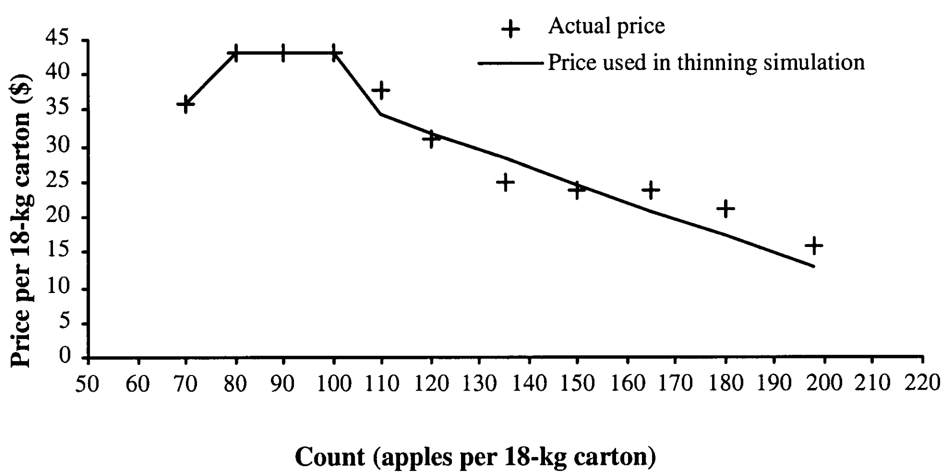

Figure 5.1: A comparison of actual price data and price relationships used in the thinning optimisation model

6. Biophysical Simulation and Sensitivity Analysis

A detailed biophysical model of an apple tree was developed in Chapter 3 and details of modelling orchard design, parameter estimation and management practices were given in Chapter 4. In this chapter the operation of the biophysical model is illustrated by solving simulations for various rootstocks. Particular aspects of the biophysical model are described in detail, including the partitioning of dry matter and the annual growth cycle of state variables. Yields from model simulations of two systems are compared with actual yield data from various similar orchard systems. Unless otherwise specified, the simulations apply to the Granite Belt region of Southern Queensland (29°S).

Sensitivity analysis of several parameters is undertaken where values were not well-defined in the scientific literature. One source of uncertainty is the partitioning of energy among tree components, a process which has not been measured in many studies. The partitioning parameters and their equations are also reviewed in this chapter and sensitivity analysis undertaken.

Uncertainty also surrounded the value of the parameter that reflects tree form, T_f, for one of the orchard systems simulated. A new value for T_f was used for this system and its selection is discussed. Sensitivity analysis of this parameter was also undertaken and is reported in this chapter.

A range of values has been reported in the literature for two important parameters: the level of root donation, ζ; and the light exposure necessary for adequate fruit colour, *uplim*. Sensitivity analysis of these two parameters was considered important and is also reported in this chapter.

6.1 Annual Growth

Using the parameters of Table 3.1 the model was used to simulate tree growth of a Granny Smith cultivar growing on the M.9 rootstock at a density of 4400 trees per hectare. Changes in each state variable in the tenth year of growth are shown in Figure 6.1. The plot shows changes in state variable mass over a single growing season.

Leaf and fruit growth follow annual cycles, starting from zero mass in spring, growing to maximum values then returning to zero values in autumn. Leaves begin to fall from the tree during late May around the time of fruit harvest in Figure 6.1. The Granny Smith cultivar is a late maturing variety and is picked during late autumn.

The mass of root and wood describe the state of an individual tree at the start and finish of each growing season and their final state determines potential growth and production in the next season. In winter and early spring these two state variables decrease in value as energy is used for respiration and is not replenished. Root mass is reduced more rapidly in early spring as reserves are used for initial leaf growth. Once leaves are able to sustain growth through photosynthesis, donation from the root system ceases and the roots and wood start to increase in mass. Steady increases in mass occur until leaves fall from the tree, at which time wood and root are no longer sustained by photosynthesis, and again lose mass as respiration demands are satisfied.

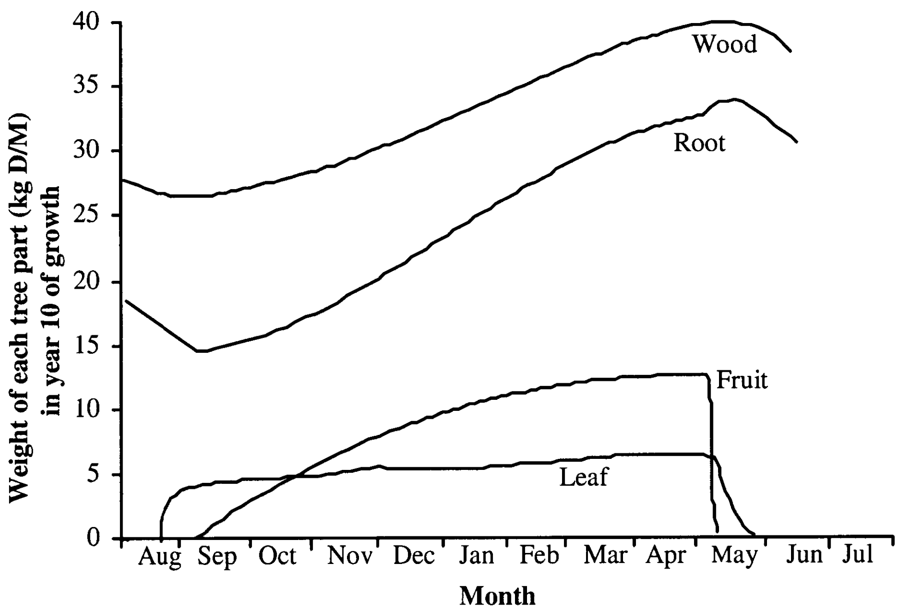

Figure 6.1. An example of changes in mass of individual tree parts during a single growing season (year 10 for Granny Smith on M.9 at 4400 trees per hectare)

6.2 System Comparison

Simulated yields for systems of interest are compared in Figure 6.2 over a period of 15 years. Granny Smith is the common cultivar simulated with each of five rootstocks. Yield differences between systems result from the range of T_f and trunk growth parameters for the given rootstock. The systems are compared from planting to maturity, and a common level of thinning (0.45) is assumed.

The highest yields per tree are grown on the MM.106 rootstock with similar yields over the initial ten years obtained with MM.104. Dramatically lower yields are obtained with the M.26 rootstock, with further decreases obtained with the M.9 rootstock at densities of 2666 and 4400 trees per hectare. Contrary to expectations, Granny Smith growing on Northern Spy produced the lowest yields; furthermore, fruit production did not begin until year six after planting. This system was expected to produce higher yields. It appears that the relatively high value of T_f for this system (0.52) is responsible for the extremely low yields. As described later, state variables are very responsive to the value of this parameter and responsiveness appears to be greater when T_f takes on values over 0.5.

Maximum steady yields are achieved earliest in the M.9 system, around year five, and maximum yields are achieved beyond year 15 for the Granny Smith cultivar growing on MM.106. The practice of thinning fruit removes most signs of biennial bearing in all systems although in the early years a slight tendency towards this habit is exhibited.

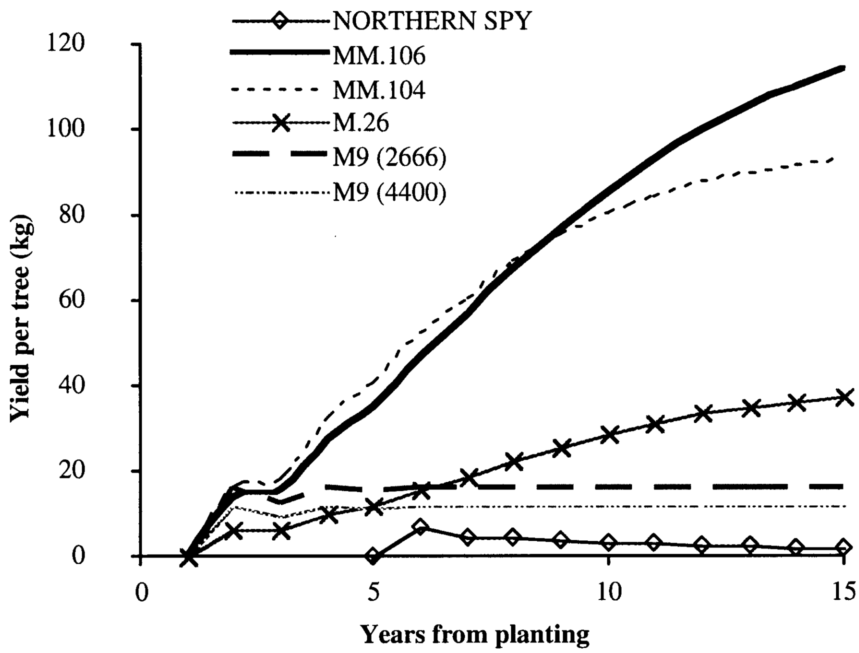

Figure 6.2. Yield per tree for various sytems

6.3 Model vs Actual Data

Yield data simulated with the model for two systems were compared with actual data. The first system is a Granny Smith cultivar growing on the MM.106 rootstock at a density of 1000 trees per hectare. Table 6.1 contains information on the model assumptions and on the various data sets used in the comparison. While none of the systems for which data are available matches the system simulated by the model exactly, those listed provide reasonable comparisons. It is important to note that location and cultivar may cause significant yield differences across rootstocks.

Yield values from the experiments and model are also compared in Figure 6.3. Trial A (Middleton, unpublished data; Middleton, 1984) provides the longest data series for comparison and is the system most closely matched to the model simulation. It is important to note, however, that no thinning took place in Trial A, hence the tendency to irregular bearing in Figure 6.3. Average yield per tree for the system simulated by the model was 55.6 kg compared to 52.0 kilograms in Trial A.

Table 6.1: Information on model simulation and actual experiments for systems on the MM.106 rootstock

Data source	Density (tr/ha)	Cultivar	Location	No. years	Cumulative yield (kg/tr)	Average yield (kg/tr)
MODEL	1000	Granny Smith	Australia	15	834.4	55.6
Trial A[ab]	997	Granny Smith	Australia	15	779.4	52.0
Hughes and Tustin (i) (1990)	635	Granny Smith	New Zealand	8	213.3	26.7
Hughes and Tustin (ii) (1990)	635	Gala	New Zealand	8	322.7	40.3

[a] No thinning occurred in Trial A
[b] Source: Middleton (1984; unpublished data)

The additional two data sets used for comparison were taken from a trial in New Zealand where trees were planted at a density of only 635 trees per hectare. Yield comparisons are provided for two cultivars: Granny Smith and Royal Gala. Cultivar differences caused significant variation in yield outcomes between the two systems at the same location. Yields in year eight for both systems were larger than those simulated with the model. This can be attributed to the lower density which results in larger trees with larger fruiting capacity.

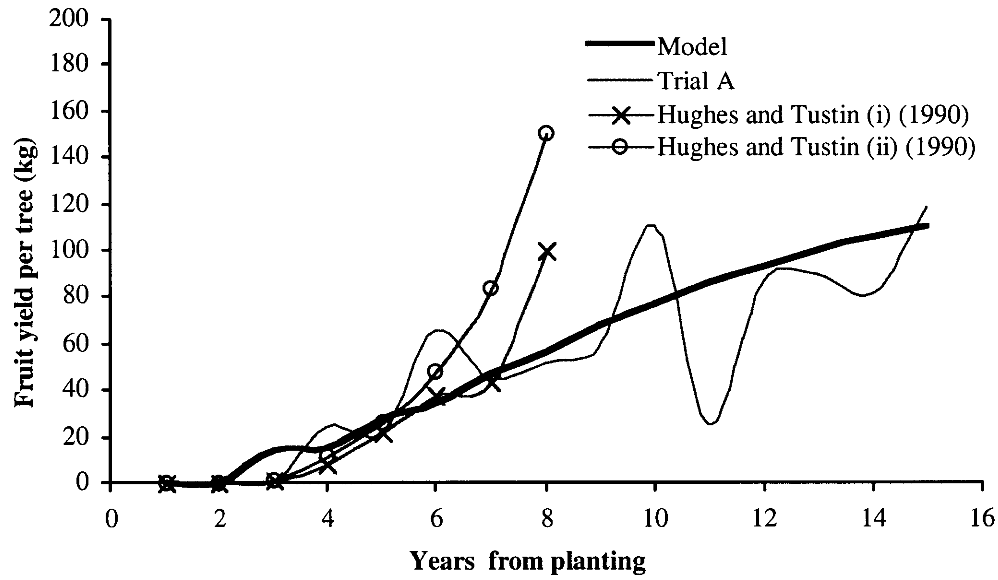

Figure 6.3. Yield comparison between the model and experimental data

The second system used to compare model results with experimental data is the high density planting of the Granny Smith cultivar on the dwarfing M.9 rootstock at a density of 4400 trees per hectare. Information on model assumptions and on the actual systems used in the comparison is listed in Table 6.2. Long-term yield comparisons are also shown in Figure 6.4. As explained later, the value of T_f for the model system was modified to 0.3, a value more appropriate to a mature tree in this sytem.

The system designs for which experimental data were obtained are, again, not perfectly matched to the system simulated by the model; however, reasonable comparisons may still be made. Costa et al. (1997) reported average tree yields of 5.1 kilograms after four years (Table 6.2) with annual yields comparing reasonably well with those from the model (Figure 6.4). Data from Hughes and Tustin (1990) are for yields spanning eight years, average yield was 6.2 kilograms compared to a higher average yield from the model of 9.2 kilograms over a period of ten years (Table 6.2). These two systems also compare reasonably well in terms of annual yield (Figure 6.4). It appears that trees in Hughes and Tustin's experiment reach a maximum yield approximately two kilograms less than that achieved in the model simulations.

Table 6.2: Information on model simulation and actual experiments for systems on the M.9 rootstock

Data source	Density (tr/ha)	Cultivar	Location	No. years	Cumulative yield (kg/tr)	Average yield (kg/tr)
MODEL	4400	Granny Smith	Australia	10	91.9	9.19
Costa et al. (1997)	4444	Average of 6	Italy	4	20.5	5.1
Sansavini and Correlli-Grappadelli. (1997)	7140	Average of 5	Italy	5	24.2	4.8
Hughes and Tustin (1990)	4500	Average of commercial plantings	Holland	8	49.5	6.2

Data from Sansavini and Correlli-Grappadelli (1997) show the lower yields per tree that result from a system that is almost twice the density to that simulated with the model. Average yields are relatively low, at only 4.8 kilograms per tree after five years (Table 6.2).

In general, model results compare reasonably well with actual experimental data despite some differences in the systems analysed.

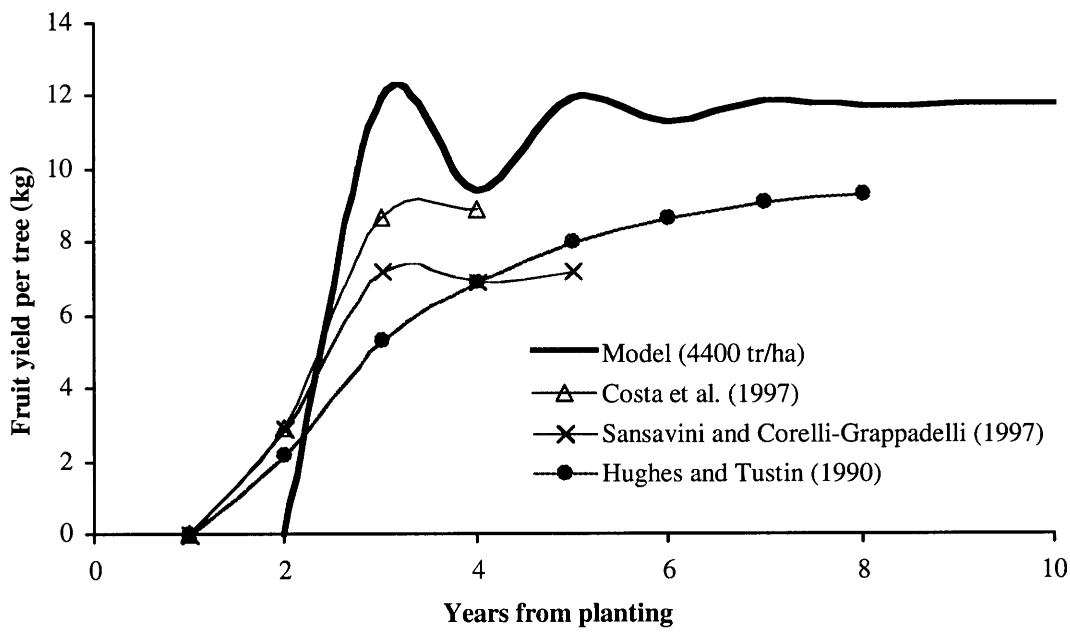

Figure 6.4. Yield comparison between the model and experimental data

6.4 Partitioning Parameters

The equations used to calculate dry-matter allocation to each tree component were based on fruit load. Equations (3.19) and (3.20) were explained in Chapter 3; they are replicated here as (6.1) and (6.2) for clarity in the discussion:

$$\rho_j = \theta_j + \frac{\lambda_j F_L}{\tau_j + F_L} \qquad \text{for } j = L, W, F \qquad (6.1)$$

$$\rho_R = 1 - \rho_L - \rho_W - \rho_F \qquad (6.2)$$

The Michaelis-Menten type equations (6.1) were calibrated based on data from Heim et al. (1979). In these equations λ_j is the maximum proportion of dry matter allocated to tree part j, τ_j is the fruit load (F_L) at which half the maximum amount is partitioned to the given tree part and θ_j is the rate of partitioning that occurs when fruit load is zero. The initial slope of each function is given by λ_j / τ_j.

In the model, fruit load is related to a specific thinning level. Thus, the pattern of partitioning is related to thinning. The partitioning functions derived using base parameter values (Table 3.1) are shown in Figure 6.5. The fruit load corresponding to each thinning level, measured as fruit number per cm^2 of trunk cross-sectional area, is shown in parentheses on the horizontal axis. The proportion of dry-matter partitioned to each tree component is measured on the vertical axis of Figure 6.5 as it relates to particular levels of thinning and fruit load.

As the thinning level increases more fruit is left on the tree and, conversely, as thinning values are reduced, less fruit is left on the tree. The value of thinning can be translated into a percentage of fruit remaining on the tree. A thinning value of one indicates 100 per cent of fruit remains on the tree ($F_L=20$) whereas a fruit load of zero indicates no fruit remains on the tree ($F_L=0$). Thinning levels between zero and one indicate various amounts of fruit remain on the tree.

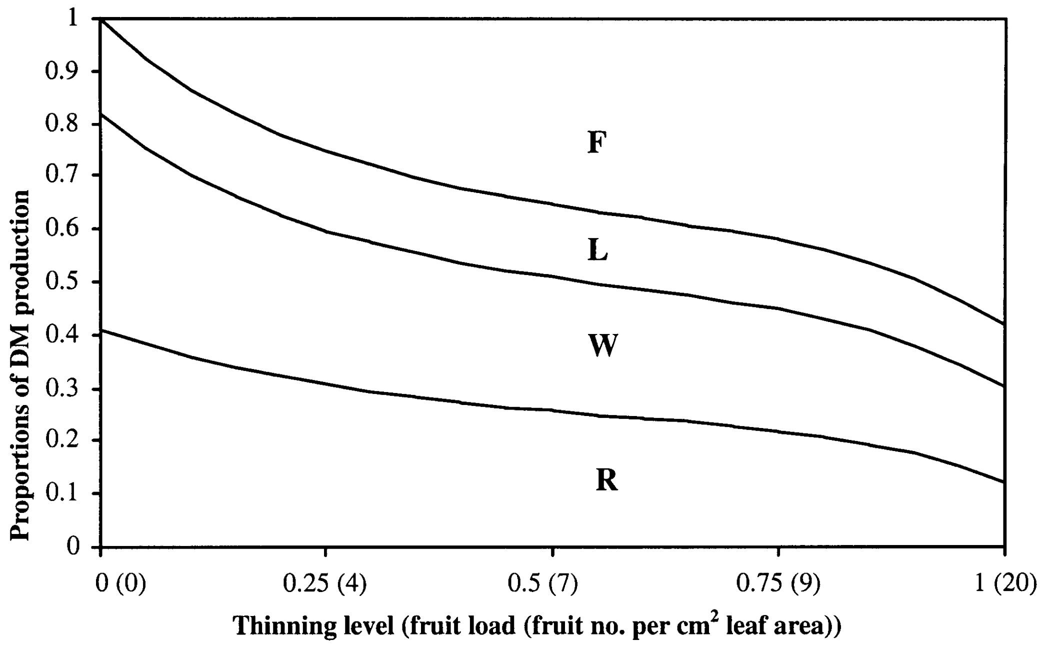

Figure 6.5: The effect of thinning level on the relative proportion of dry matter partitioned to each tree component: fruit (F), leaf (L), wood (W) and root (R)

When all fruit is left on the tree almost 60 per cent of dry matter growth is partitioned to the fruit with the remaining 40 per cent divided up between the remaining three components. The leaves receive 12 per cent, the wood receives 18 per cent and the remaining dry matter is partitioned to the root. Conversely, when no fruit is present on the tree approximately 20 per cent, 40 per cent and 40 per cent of dry matter is partitioned to the leaf, wood and root, respectively.

As the amount of fruit on the tree increases (the thinning level increases), dry-matter partitioning to root is the most affected, followed by partitioning to wood. The proportion partitioned to the leaf is practically unaffected.

Sensitivity analysis on the partitioning parameters, θ_j, λ_j and τ_j,, was undertaken for leaf, wood and fruit in turn. The effects on state variables in year ten after planting were analysed for a ten per cent increase or decrease in each parameter value. The level of thinning for sensitivity analysis was fixed at 0.45.

6.4.1 Leaf parameters

Results for sensitivity analysis on leaf partitioning parameters are given in Table 6.3. The values of all state variables represent their maximum annual value during year ten. Elasticity values were calculated as the percentage change in the state variable divided by the percentage change in the partitioning parameter. Thus, the elasticity of a particular state variable (j) with respect to changes in θ_L is calculated as:

$$elasticity = \frac{newj - basej}{basej} \Bigg/ \frac{new\theta_L - base\theta_L}{base\theta_L} \tag{6.3}$$

In general, state variables are inelastic with respect to changes in leaf partitioning parameters. That is, they are relatively unresponsive to changes in parameter values (Table 6.3).

Elasticities were positive for changes in both θ_L and τ_L, so that, as these parameters increased (decreased) the value of the state variables also increased (decreased). Higher values of dry matter partitioned to leaf when fruit load is zero are the result of increasing θ_L and lead to greater potential photosynthesis and growth of all tree parts. Higher values of τ_L result in half of the maximum partitioning being undertaken at a higher fruit load and results in increased mass of each state variable. In contrast, the elasticities with respect to λ_L, were negative and very low, hence the effects of changing this parameter were minimal.

Both a ten per cent increase and a ten per cent decrease are reported for θ_L because the resulting elasticities were not symmetric. The ten per cent decrease in the parameter results in a higher elasticity than the corresponding ten per cent increase in the parameter, although elasticity values are well below one indicating state variables are relatively unresponsive to changes in this parameter.

Table 6.3: Sensitivity of maximum values of state variables in year ten to changes in leaf partitioning parameters

		θ_L change				τ_L change		λ_L change	
		↓10%		↑10%		↓10%		↓10%	
State variable	Base value (kg DM)	value (kg DM)	elasticity	value (kg DM)	elasticity	value (kg DM)	elasticity	value (kg DM)	elasticity
Fruit	12.85	12.44	0.32	13.11	0.20	12.81	0.03	12.92	–0.05
Leaf	6.14	6.02	0.18	6.20	0.10	6.12	0.02	6.15	–0.03
Wood	37.45	35.76	0.45	38.67	0.32	37.28	0.05	37.76	–0.08
Root	30.25	28.93	0.44	31.17	0.31	30.11	0.05	30.11	–0.05

Table 6.4: Sensitivity of maximum values of state variables in year ten to changes in wood partitioning parameters

		θ_W change				τ_W change		λ_W change	
		↓10%		↑10%		↓10%		↓10%	
State variable	Base value (kg DM)	value (kg DM)	elasticity	value (kg DM)	elasticity	value (kg DM)	elasticity	value (kg DM)	elasticity
Fruit	12.85	12.76	0.08	12.94	0.07	12.83	0.01	12.89	0.33
Leaf	6.14	6.12	0.03	6.15	0.02	6.13	0.01	6.14	–0.01
Wood	37.45	31.03	1.72	44.04	1.76	36.2	0.33	39.88	–0.65
Root	30.25	32.88	–0.87	27.52	–0.90	30.76	–0.17	29.25	0.33

Table 6.5: Sensitivity of maximum values of state variables in year ten to changes in fruit partitioning parameters

		λ_F change				τ_F change			
		↓10%		↑10%		↓10%		↑10%	
State variable	Base value (kg DM)	value (kg DM)	elasticity	value (kg DM)	elasticity	value (kg DM)	elasticity	value (kg DM)	elasticity
Fruit	12.85	11.64	0.94	14.04	0.93	13.62	–0.60	12.16	–0.54
Leaf	6.14	6.15	–0.02	6.12	–0.02	6.13	0.02	6.14	0.01
Wood	37.45	37.94	–0.13	36.95	–0.14	37.13	0.09	37.74	0.08
Root	30.25	33.05	–0.93	27.48	–0.91	28.46	0.59	31.85	0.53

Table 6.6: Sensitivity of state variables (j) to changes in T_f, assuming base T_f is 0.37, minimum TCSA for bearing is 700 cm^2 and system is Granny Smith/M9 at a density of 4400 trees/ha

		T_f change							
		↓20%		↓10%		↑10%		↑20%	
State variable	Base value (kg DM)	value (kg DM)	elasticity	value (kg DM)	elasticity	value (kg DM)	elasticity	value (kg DM)	elasticity
Fruit [a] [b]	76.73 [b]	104.96 [b]	–1.84	91.34 [b]	–1.9	60.61 [b]	–2.1	42.42 [b]	–2.24
Leaf	6.14	0.81	–0.2	0.80	–0.28	0.73	–0.59	0.63	–0.96
Wood	37.45	5.79	–2.15	4.94	–2.18	3.12	–2.31	2.09	–2.4
Root	30.25	4.44	–2.19	3.78	–2.24	2.34	–2.40	1.53	–2.52

a Cumulative 10 year yield per tree.
b Measured in terms of kg fresh weight.

6.4.2 Wood parameters

Results of sensitivity analysis on the wood partitioning parameters are shown in Table 6.4. Elasticity values for wood with respect to θ_W are greater than unity implying that changing the maximum portion of dry matter partitioned to wood has a more than proportional effect on wood mass. The remaining elasticities are below one, thus the remaining state variables are not very responsive to changes in this parameter. The elasticity of root mass with respect to θ_W and τ_W is negative. This result is not surprising as wood and root compete with each other for carbohydrates produced by photosynthesis. In the case of λ_W, it is leaf and wood mass that change in the opposite direction to changes in the parameter, while root mass changes in the same direction.

6.4.3 Fruit parameters

The responsiveness of state variables to changes in the fruit partitioning parameters are given in Table 6.5. Only two partitioning parameters are relevant in this case, λ_F and τ_F. The absolute value of all elasticities is below unity implying that changes in each parameter have a less than proportional effect on mass of each state variable. Despite this, the elasticity of root mass and the absolute value of fruit mass with respect to λ_F and τ_F.are very close to unity, with values of approximately 0.94 and 0.92, respectively. Elasticity values equal to unity would indicate that a one percent change in the parameter results in an equivalent one percent change in the mass of a given state variable.

The elasticities of leaf, wood and root mass with respect to λ_F are negative, whereas the elasticity of fruit mass with respect to this parameter is positive. This result is not surprising since increases in λ_F indicate a higher proportion of dry matter is partitioned to fruit at the expense of all other state variables. The increase in dry matter partitioned to fruit allows a greater fruit mass to grow on the tree hence the positive elasticity. In contrast, the elasticity of fruit mass with respect to τ_F is negative, whereas the elasticities of all other state variables with respect to τ_F are positive.

6.5 Light Interception

The values of the parameter used as a proxy for tree form in the orchard, T_f, were calculated from measurements of light interception (Middleton, unpublished data; Middleton, 1997; Middleton, 1999). Light interception measurements were taken when trees were mature in all cases but one, when cultivars were growing on the M.9 rootstock trained to the V-trellis at a density of 4400 trees per hectare. The relatively high value of T_f (0.59) calculated from light measurement data for this system was taken when the trees were two years old. Since $(1-T_f)$ gives the amount of light interception by each tree in the orchard, cultivars on M.9 are simulated as intercepting only 41 per cent of light at two years of age. Questions arise as to the value of T_f that will be achieved when the trees are mature.

Little published data are available on how light interception changes as an apple tree grows. The literature states that T_f (and hence light interception) is determined, among other factors, by tree height (Jackson and Palmer, 1979) hence age is an important factor. A comparison of various systems over time suggests that as trees age and increase in size, light interception increases and hence T_f decreases (Jackson, 1980a). It seems unlikely, therefore, that the value of T_f for mature trees growing on the M.9 rootstock will remain at the relatively high value assumed in the model. This was confirmed by Middleton, S.G. (1999, pers. comm.) and a value of 0.3 was suggested by Middleton as the appropriate value for mature trees in this system. This value was used in model simulations of this system in Section 6.3 and later chapters.

Sensitivity analysis on the value T_f was undertaken using a Granny Smith cultivar growing on the M.9 rootstock and planted at a density of 4400 trees per hectare. The value of T_f was varied, and cumulative fruit yield was estimated through simulation with results shown graphically in Figure 6.6.

Changes in T_f have a dramatic effect on cumulative fruit production, with yields rapidly decreasing as T_f increases from 0.25 to 0.5 (Figure 6.6). Because of the nonlinear nature of this relationship, sensitivity calculations were obtained for increases and decreases of both 10 and 20 per cent; results are presented in Table 6.6. Elasiticies were calculated according to equation (6.3).

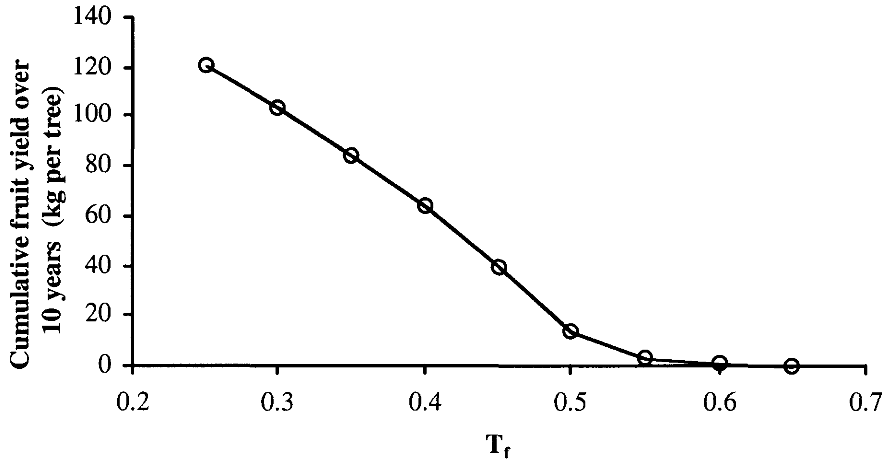

Figure 6.6. The relationship between T_f and cumulative fruit production

As expected, all elasticities were negative, regardless of magnitude and direction of change in parameter value. Thus, in every case an increase (decrease) in T_f caused a decrease (increase) in the value of each state variable. This result is not surprising since higher values of T_f reflect lower levels of light interception. Reduced light interception results in less photosynthesis and thus less energy for growth of each tree part.

Changes in T_f produced large responses in fruit, wood and root mass, the latter being the most responsive. The responsiveness of root mass appears to increase as the increase in T_f becomes larger. A ten per cent increase in T_f results in an elasticity of -2.40 while a 20 per cent increase in the parameter produces an elasticity of -2.52. This pattern of response to changes in T_f is also reflected in the elasticity values of the other state variables.

Elasticities with respect to a particular state variable are not equivalent when parameter changes are of the same magnitude but opposite in direction. For example, a ten per cent decrease in T_f results in an elasticity with respect to fruit mass of -1.9 while a ten per cent increase in the parameter produces an elasiticity of -2.1. This phenomenon is common to all state variables as T_f changes by equal amounts that are opposite in direction. Furthermore, as the percentage change in T_f is reduced from 20 per cent to ten per cent, the effect on the mass of each state variable is also reduced.

The results from Figure 6.6 and Table 6.6 indicate that all state variables are extremely responsive to the value of T_f. Accurate measurement of this parameter is therefore crucial if the model is to be an accurate predictor of orchard system productivity and profitability.

6.6 Reserve Donation and Requirements for Good Colour

Two additional parameters were subjected to sensitivity analysis because of the wide range of values reported in the literature. The parameters were *uplim,* the minimum light exposure necessary for adequate fruit colour, and ζ, the level of root donation.

The value of *uplim* is used in equation (3.24), where L_{uplim} determines the light exposure necessary for adequate fruit colour. In the base model simulations *uplim* has a value of 0.3 indicating that 30 per cent light exposure is required for adequate fruit colour. The value of *uplim* varies across locations (Jackson, 1997).

Sensitivity analysis was used to investigate the responsiveness of state variables to changes in *uplim.* The parameter was increased and decreased by ten per cent and results are shown in Table 6.7. All elasticities are negative which indicates that as the parameter value is increased (decreased) the values of the state variables decrease (increase). When *uplim* increases, adequate light exposure is reduced thus reducing photosynthesis and dry matter allocation to each plant part. Fruit and leaf mass are the least responsive to changes in the parameter, with elasticity values of less than unity, although the elasticity of fruit mass is close to unity. Wood and root mass, the perennial parts of the apple tree, are very responsive to changes in the parameter with elasticity values greater than unity. Sensitivity analysis on this parameter suggests that its value is important and should be accurately measured for each location.

Table 6.7: Sensitivity of maximum values of state variables in year ten to changes in the parameters *uplim* and ξ, for Granny Smith on MM.106 at 1000 trees per ha

		***uplim* change**				**ζ change**	
		↑10%		↓10%		↓20%	
State variable	Base value (kg DM)	value (kg DM)	elasticity	value (kg DM)	elasticity	value (kg DM)	elasticity
Fruit[a,b]	425.73	464.1[b]	–0.90	386.14[b]	–0.93	404.80[b]	0.25
Leaf	6.14	6.19	–0.08	6.06	–0.13	3.04	0.08
Wood	37.40	41.26	–1.03	33.52	–1.04	34.26	0.42
Root	30.23	33.35	–1.03	27.06	–1.05	27.86	0.39

[a] Cumulative 10 year yield per tree.

[b] Measured in kg fresh weight.

Hansen (1977) reports that the value of ζ ranges from 0.04 to 0.05, and the latter value was used in the simulation of all orchard systems. Sensitivity analysis was used to investigate the effect of reducing ζ by 20 per cent to 0.04. The effect on each state variable from this change is shown in Table 6.7. All elasticities are positive and below one. Reducing the amount of root donation that occurs during spring reduces the mass of all four state variables, although by proportionately less than the reduction in ζ.

6.7 Summary

The biophysical simulation model was analysed in detail in this chapter. Importantly, yields from model simulations of two orchard systems were compared with yield data obtained from actual experiments undertaken with similar systems. In general, comparisons showed that the biophysical model is able to simulate fruit yield for given orchard systems with reasonable accuracy.

Sensitivity analysis was undertaken on several parameters where a degree of uncertainty surrounded their values. These parameters are those responsible for dry matter partitioning (λ_j, τ_j, and θ_j), light interception (T_f), the parameter describing the minimum light exposure necessary for adequate fruit colour (*uplim*) and donation of carbohydrates from the root system (ζ).

Sensitivity analysis of T_f showed that all state variables are extremely responsive to its value. Accurate measurement of this parameter is therefore crucial if the model is to be an accurate predictor of orchard system productivity and profitability. Furthermore, field research that investigates how the value of T_f changes as apple trees in different systems age is likely to increase the accuracy and predictive ability of the biophysical model.

Likewise, the value of *uplim* has a significant effect on several state variables. Since the value of *uplim* is known to vary across locations, field research that provides information on how this parameter varies is likely to enhance the usefulness of the biophysical model.

7. Economic Model: Optimal Thinning Strategy

The economic model developed in this chapter describes the costs and revenues associated with one particular orchard system from planting to maturity. The economic model is integrated with the biophysical model and then used to maximise net present value by selecting optimal thinning strategies over a 15–year period. Various solution techniques are discussed and used in model optimisation. Thinning is also investigated in a non-optimising framework. The model described in this chapter provides the basis for the applications described in later chapters.

7.1 Conceptual 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 7.1. 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 thinning application of this chapter.

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.

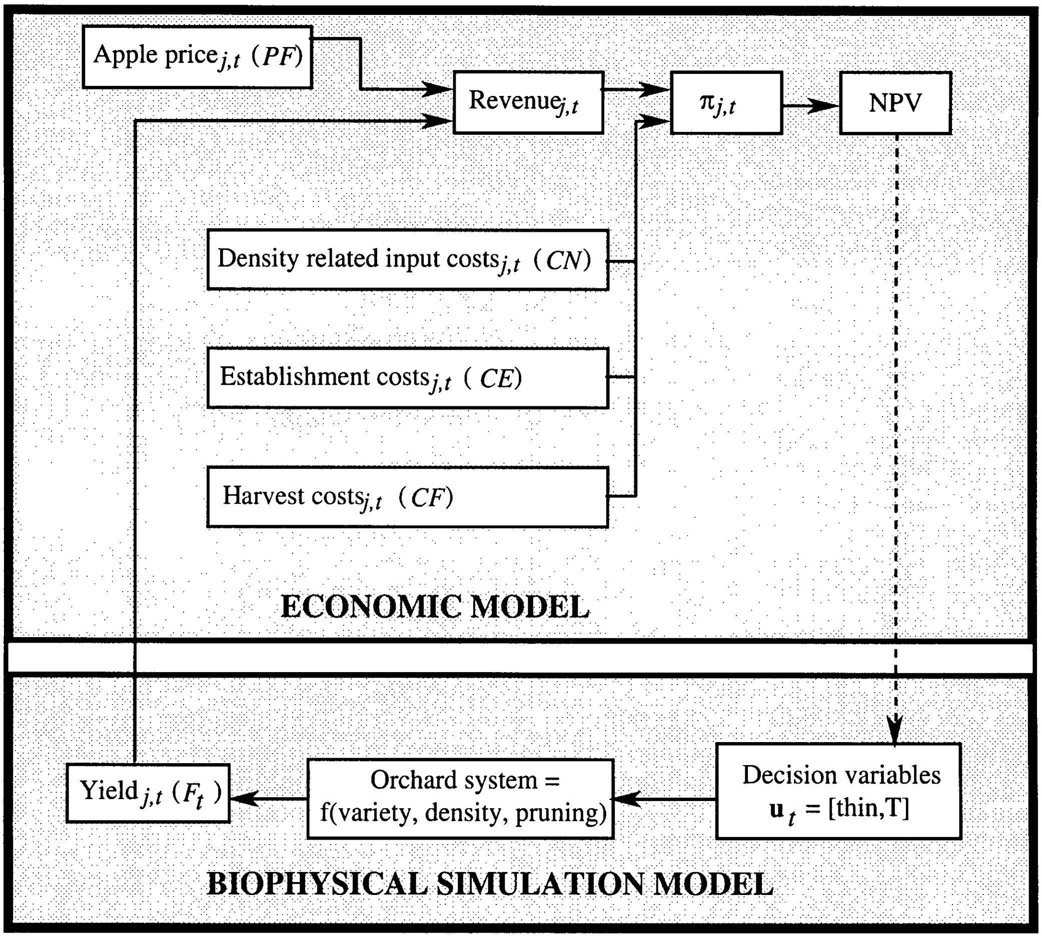

Figure 7.1: Diagrammatic representation of the bioeconomic model (j=variety, t=year)

7.2 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:

$$V = \sum_{t=1}^{T} \pi_t\left(F_t\left(\mathbf{x}_t, \mathbf{u}_t\right)\right)\frac{1}{\left(1+r\right)^t} - CE \tag{7.1}$$

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:

$$\pi_t = \left(PF\left(w_F\right) - CF\right).F_t\left(\mathbf{x}_t, \mathbf{u}_t\right) - N.CN_t\left(A_t\right) \tag{7.2}$$

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. Note that price is determined by fruit weight, as explained in Chapter 4. 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:

$$F_t = N\sigma \int_{\tau=t}^{t+1} \left[\left(P_{d\tau} - R_{dF\tau} \right) \psi + CHO\tau \right] \rho_{F\tau} \left(\mathbf{x_t}, \mathbf{u_t} \right) d\tau \qquad (7.3)$$

where τ represents time measured in days. 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, depends on state and control variables and these relationships are quite complex, as described in Chapter 3. Equation (7.3) is based on (3.1) from the biophysical model. The parameter σ, as defined in Chapter 3, 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, (3.1), 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:

$$\mathbf{x_t} = [R_t, W_t, D_t] \tag{7.4}$$

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:

$$\mathbf{u_t} = [thin_t] \qquad 0 \leq thin_t \leq 1 \tag{7.5}$$

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.

This annual objective 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.

The simulation provides the level of thinning in each year that maximises NPV given the inherent tendency towards biennial bearing in the biophysical model. This innovation in the model, to incorporate the biennial bearing habit and optimise decisions influencing it, represents a significant contribution to understanding of the apple orchard problem.

7.2.1 Biennial bearing and fruit size

The bioeconomic model, as used in this application, consists of equations (7.1) to (7.3) and the vectors represented in (7.4) and (7.5). Biennial bearing was introduced into the model in Chapter 4, using the equation:

$$EFL_t = \left(BFL - \left(F_{L_{t-1}} - BFL\right)\right) \tag{4.1}$$

where EFL_t is expected fruit load, BFL is fruit load that would lead to minimal or no biennial bearing and F_{Lt-1} is fruit load in the previous year.

As described in Chapter 4, the process of thinning results in a proportion of the original amount of fruit on the tree. The actual fruit load that results from thinning, (F_{Lt}), is calculated as:

$$F_{L_t} = EFL_t \,.\, thin_t \qquad\qquad 0 \le thin_t \le 1 \tag{4.2}$$

Once FL_t is determined, fruit number *(FN)* is calculated according to:

$$FN_t = F_{L_t} \,.\, LA_{\max_t} \tag{4.3}$$

where LA_{max_t} is the maximum leaf area, calculated from equation (3.17). Finally, average fruit weight $\left(FW_t\right)$ is calculated as:

$$FW_t = \frac{Y_{Ft}}{FN_t} \tag{4.4}$$

FW_t is used to determine price per kilogram as discussed in the following section.

7.3 Prices

The price-count relationships outlined in equation (5.1), Figure 5.1 and Table 5.12 are adopted in determining the optimal thinning strategy. The price differences between apple sizes are important in determining the thinning strategies that maximise profit over time. As discussed in Chapter 5, it is assumed that the price relativities are independent of maximum price level, hence the price line in Figure 5.1 moves vertically. If price relativities between different sized fruits are independent of maximum price levels, it also follows that the optimal thinning strategy will not change with the maximum price level. Thus, the position of the price line on the vertical axis is not crucial to determining the optimal thinning strategy, rather, it is the method used to determine price relationships in (5.1) that is crucial. However, the vertical position of the price line does influence NPV over the time frame simulated.

7.4 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 Chapter 5, Table 5.1.

Labour time required for cultural practices, planting and other orchard tasks are described in Tables 5.4 and 5.5 of Chapter 5. All labour in the one-hectare orchard is priced at the casual rate of A$11.11 per hour.

The chemical and fertiliser regimes followed during the lifetime of the orchard are those discussed in Chapter 5. Costs related to tree density (*CN*) are presented in Figure 7.2 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. Assumptions about parameter values that are specific to the simulation are listed in Table 7.1 with values of non-system specific parameters listed in Table 3.1 of Chapter 3.

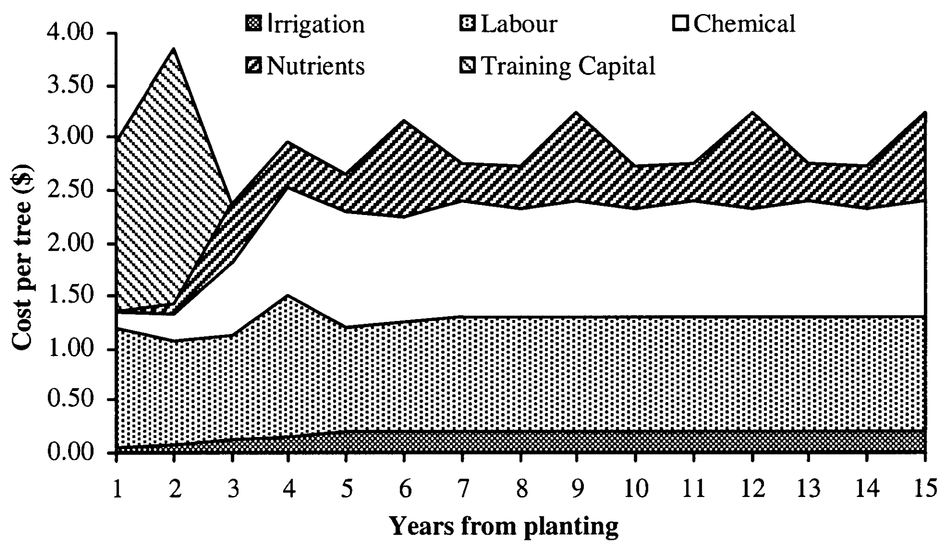

Figure 7.2: Density related costs (*CN*) over the simulation period

The biophysical model, described by equation (7.3) and discussed in Chapter 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.

Table 7.1: System specific parameter values used in base model run

		Parameter	Value
Orchard design			
	Trees/hectare	N	1000
	Light missing tree	T_f	0.31
Price			
	Bin harvest cost ($)	CF	23.17
	Interest rate (%)	r	6.0
Initial values of state variables			
	Leaf	L_0	0
	Wood	W_0	90
	Root	R_0	150
	Fruit	F_0	0
Fruit load and thinning			
	Best fruit load	BFL	10
	Initial reserves	$DMmax_0$	72
Trunk growth			
	Initial TCSA (cm^2)	$TCSA_0$	1.57
	Relative growth rate	μ	1.00
	Decay in specific growth rate	δ	0.22

7.5 Solution Techniques

Various solution techniques are available to optimise the dynamic bioeconomic model described in Section 7.2: dynamic programming; non-linear programming; and genetic algorithms.

Dynamic programming (DP) is a solution technique for solving multi-stage decision problems and was originally developed by Bellman (1957). In the DP approach, the optimisation problem is decomposed into stages where the outcome of a decision at one stage affects the results and decisions made in the following stage. Solutions to the problems are obtained recursively by repeated solution of an 'optimal value function', firstly by proceeding backwards in time to determine a set of optimal decision rules, and secondly, by using the optimal decision rules to determine the optimal path for given initial conditions (Cacho, 1998).

While DP can solve what would otherwise be unwieldy problems, it has as its main disadvantage the 'curse of dimensionality' (Cacho, 1998). The solution of the DP problem starts by creating a 'state grid', where each dimension represents a state variable and each point on the grid represents a different combination of state variable values. The biophysical model is repeatedly solved at each point on the grid in order to find optimal values of the vector of control variables at each given state. Cacho (1998) illustrates the explosive growth in complexity of DP models as the number of state and control variables increases. The example used in Cacho (1998) is modified here to reflect the dimensionality problem when the current model is solved using DP. In the DP framework the model contains four state variables (root, wood, *CHO* reserves, and fruit load in the previous year) and one control variable and is solved over a 15-year time horizon. If each state in the problem is sampled using a small number of points, say five, the state grid has 625 (5^4) points per time period, which means the optimal value function is solved 9,375 times. In solving the optimal value function to find a maximum, the biophysical model is solved repeatedly. Finding maximum NPV involves obtaining the optimal value of the control variable for each given state, hence the control space is sampled at regular intervals to select the best value of the control vector. If each of the control variables is sampled for a minimum of six values, resulting in six function evaluations per state, it translates into a total of 56,250 ($15 \times 5^4 \times 6^1$) runs of the annual biophysical model in order to solve the DP model. If it takes 12 seconds to solve one run of the biophysical model, it would take almost eight days to solve a single run of the deterministic model. Optimal results for thinning would be improved by increasing the sample points for each of the state and control variables, and hence would require even greater computer time.

Given demands on computer time necessary to solve the current model as a DP, this solution technique was not considered further.

Non-linear programming (NLP) is the second solution technique considered for optimising the current model. Using the NLP technique the number of decision variables is determined by the number of control and state variables multiplied by the number of time periods in the planning horizon (Cacho, 1998). In the current model the number of control variables increases to a maximum of 15, or less if fruiting does not occur in a particular year.

The model was solved as a NLP problem based on a sequential quadratic programming algorithm (Mathworks, 1996b). Optimisation was achieved by incorporating function (7.1) in a constrained maximisation model with a discount rate of six per cent. The problem took over 2000 iterations to converge to an optimal solution when solved as an NLP. A common problem with complex NLP models is the difficulty of finding a global maximum. Indeed, when the model was solved over aperiod of 15 years there was a tendency for the algorithm to converge to what later was confirmed to be a local maximum. With this in mind, the solution of the NLP problem is compared to the final solution technique under consideration, the genetic algorithm method.

A genetic algorithm (GA), based on the evolution of populations of living organisms, is a technique that may be used to maximise functions that are highly non-linear or which have a large number of control variables (Cacho and Simmons, 1999). The following discussion of GA models is based on Cacho (1998). The GA starts with a population of 'random individuals' that contain genes representing thinning levels over 15 years, each gene represents a possible solution to the maximisation problem. Following thinning and tree growth over 15 years each individual receives a 'fitness score', which is based on NPV and is directly determined by that individual's gene.

Individuals are given the opportunity to reproduce by cross-breeding with other individuals in the population where the probability of reproduction is directly related to fitness score. Thus, the 'fittest' individuals (those that produce the highest NPV) have a higher probability of being selected for breeding than the 'weak' individuals (those with low NPV resulting from the thinning strategy encoded in their genes). The new generation inherits traits from both parents. A small portion of the new generation may also undergo random mutation. Over a particular number of generations good characteristics (profitable thinning rates) are spread throughout the population as less fit members die out. Ultimately, the population converges to a level of fitness close to the maximum NPV which results from a quasi-optimal vector of decision variables. The GA used to maximise NPV by optimising annual thinning rates is based on that used in Cacho and

Simmons (1999). Values of important parameters are given in Table 7.2. Because the GA is based on probabilities, the problem was solved repeatedly (33 times) using different random seeds to initialise the random number generator each time. Each run of the GA resulted in a different final uniform population whose genes produce an NPV which is close to the maximum value of the objective function.

Table 7.2: Values of key variables used in the Genetic Algorithm

Parameter	Value
Number of generations	600
Initial population size	200
Number of expected children from best individual	2
Mutation probability	0.01
Crossover probability	0.6
Number of random seeds	33

7.6 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, on fruit weight, average price, average yield and NPV were investigated. Results of this analysis are shown in Figure 7.3.

Average fruit weight decreases in a non-linear fashion (Figure 7.3 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 growth 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 7.3 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 7.3 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 7.3 D) to a maximum and decreases thereafter. Prior to the level of thinning that produces maximum NPV (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.

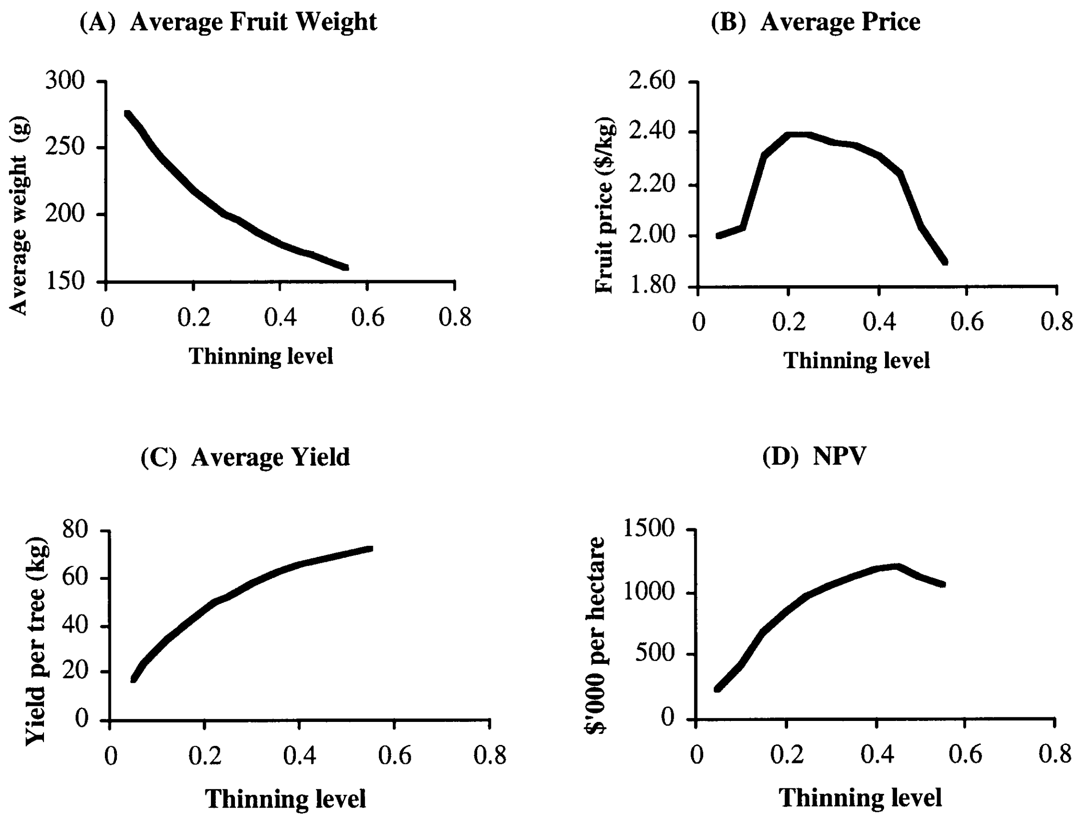

Figure 7.3: The effect of thinning on average fruit weight (A), price (B), yield (C) and NPV (D)

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.

7.7 Dynamic Optimisation Results

The model was optimised using the GA and NLP procedures and results of each solution technique are compared in this section. As mentioned earlier, the GA was run 33 times with each run resulting in different final values of NPV, fruit weight, fruit price, yield and optimal thinning rates. For the purposes of comparing solution techniques, the GA run that resulted in the highest NPV is called 'GA Best', the average of 33 GA runs is called 'GA mean' and results from the NLP are called 'NLP'. In the search for the true global maximum, the optimal thinning values from GA Best were entered as starting values into an additional NLP optimising run. This run is called 'NLP Best' and is discussed only in terms of NPV and optimal thinning trajectories.

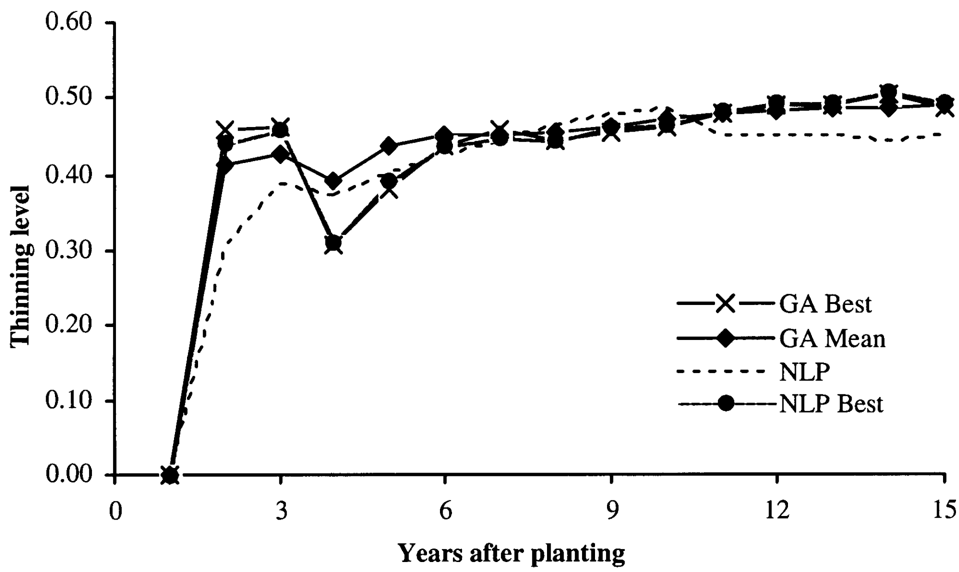

Figure 7.4: Optimal thinning rates that result from optimising the model using a GA and NLP

Optimal thinning trajectories obtained with each optimisation routine are compared in Figure 7.4. Optimal thinning rates from a given routine show variation until year five but become relatively stable thereafter. It is interesting to note that the optimal thinning trajectory found by NLP best is very close to that of GA best.

Despite early differences in optimal thinning rates between routines, cumulative fruit yield and NPV from each routine are quite similar (Table 7.3). Highest fruit yields were obtained by NLP Best, followed by GA mean, GA Best and NLP. NPV is maximised with the thinning trajectory of NLP Best (A$1,268,000). NPV resulting from GA Best, GA mean and NLP are respectively A$1,264,660, A$1,234,190 and A$1,233,260. The results suggest that NLP Best represents the global maximum and shows that a combination of GA and NLP can decrease the possibility of convergence to a local maximum common in traditional NLP models.

Table 7.3: Comparison of cumulative fruit yield and NPV for each optimising routine

	Cumulative 15 year fruit yield (kg/tree)	NPV (A$'000/ha)
GA Best	966.6	1264.66
GA Mean	968.6	1234.19
NLP	950.9	1233.36
NLP Best	969.2	1268.11

Figure 7.4 contains a series of comparisons between GA Best, GA mean and NLP for yield, fruit weight, fruit price and the discounted value of profit. Results from NLP Best are not shown because they practically overlap those of GA Best. Annual fruit yield per tree shows little variation across optimising routines (Figure 7.5A). Differences in average fruit weight per tree are evident in years one to five between routines (Figure 7.5B), and this reflects differences in the optimal thinning rates in these early years. However, beyond year five average fruit weight shows little difference across optimising routines.

Marked differences are evident when prices per kilogram of fruit are compared (Figure 7.5C). Under GA Best, only one price below the maximum level occurs (year two) with price at the maximum level in all remaining years. This is not the case for either GA mean or NLP, where prices fall below the maximum levels in several years.

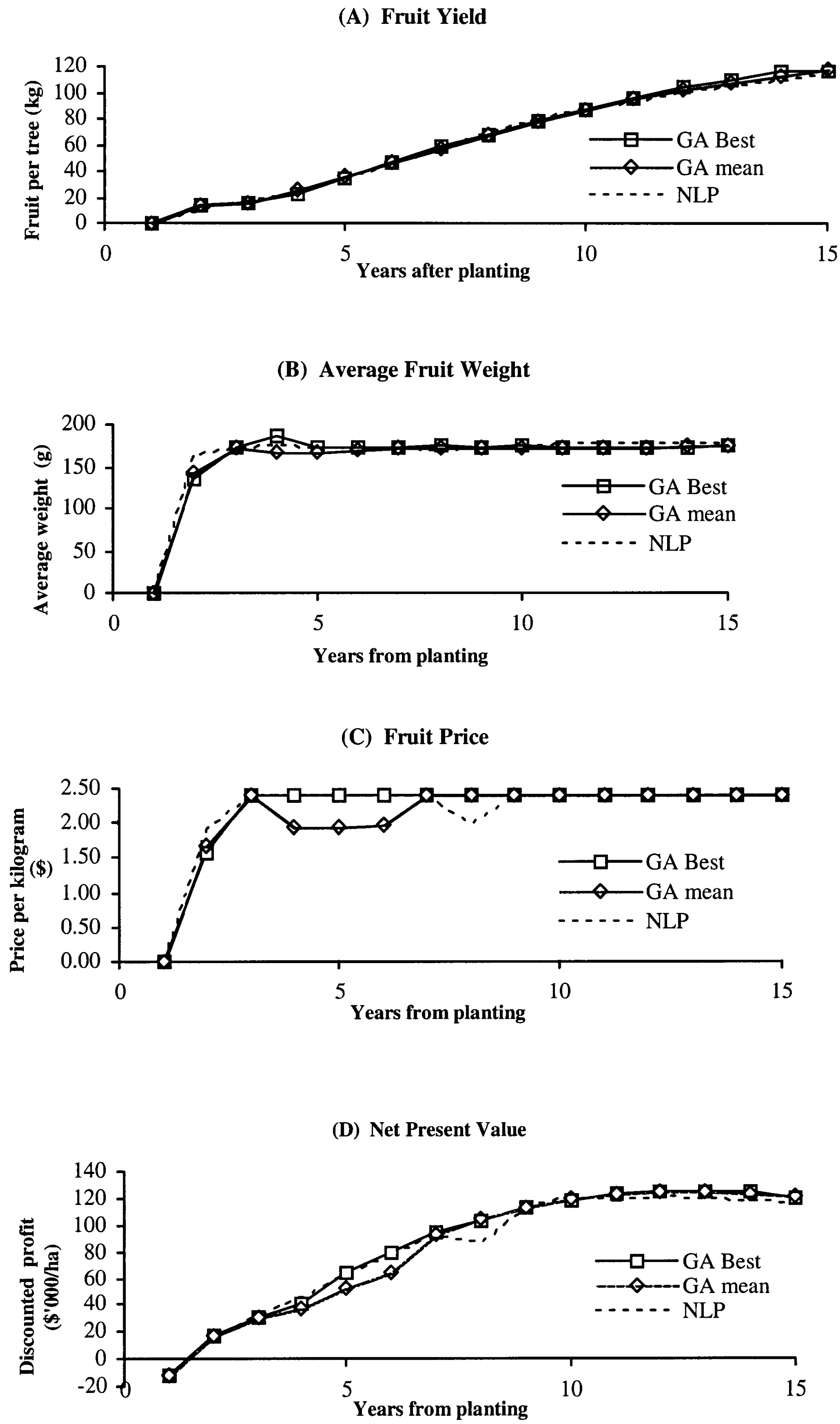

Figure 7.5: Comparison of the effect of optimising routine on fruit yield (A), fruit weight (B), fruit price (C) and Net Present Value (D)

Annual discounted profits are affected by fruit prices resulting from each thinning strategy (Figure 7.5 D). Before the trees begin to bear fruit, initial establishment costs and variable costs result in a negative profit. Annual profit measured using the GA mean and NLP drops below that of the GA Best in those years where price also drops below the maximum level, hence the lower value of NPV for GA mean and NLP (Table 7.3).

Yield results over 15 years from GA Best are compared with a situation of no thinning in Figure 7.6. 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 GA Best thinning strategy, where the cycle of dramatic fluctuation is eliminated.

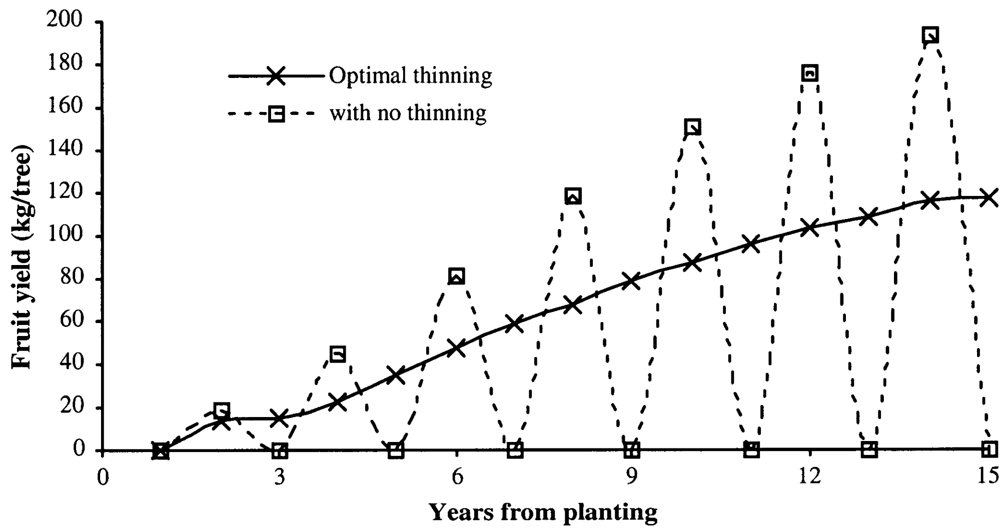

Figure 7.6: Annual fruit yield with optimal thinning strategy and no thinning

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 7.7. When no thinning occurs, the 'on' years produce a fruit load of 20 fruits per m^2 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 m^2 of leaf area. Small fluctuations occur in the earlier years but are reduced to almost no variation by year ten.

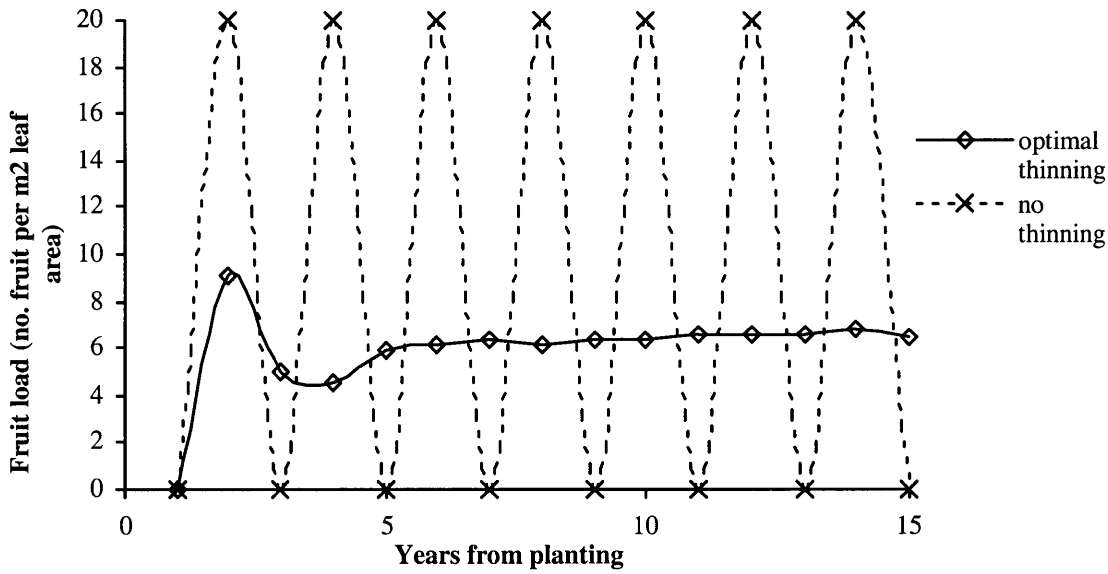

Figure 7.7: Comparisons of fruit load from no thinning and the optimal thinning strategy

7.8 Summary

The objective of this chapter was to describe the economic model and use it to investigate thinning strategies for one particular orchard system. 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.

Various solution techniques were available to optimise the dynamic economic model. Of these techniques, GA and NLP procedures were used to maximise NPV by selecting the optimal values of thinning in each year of the 15-year planning horizon. Both solution techniques were able to provide similar optimal thinning results, although the highest NPV was obtained from one particular run of the GA. When these thinning values were entered as starting values in an additional NLP run, NPV improved and the result was assumed to be the true global maximum. This additional simulation also showed that a combination of GA and NLP can decrease the possibility of a convergence to a local maximum common in traditional NLP models.

The optimal thinning trajectory removed the dramatic fluctuations in fruit yield and fruit load that would otherwise occur if all fruit remained on the tree. The optimal thinning trajectory resulted in fruit load settling at a value of six fruits per m^2 of leaf area.

8. Comparing System Profitability

Various orchard systems were outlined in Chapter 5 with the aim of simulating the profitability of each. Simulation of NPV for each system is carried out in this chapter, assuming there is certainty about the future. Yield and optimal thinning rates are also compared between systems.

8.1 Simulation Design

The systems consist of five cultivars (Hi-Early Red Delicious, Granny Smith, Pink Lady, Fuji and Gala) growing on five rootstocks (M.9, M.26, MM.104, MM.106 and Northern Spy), making a total of 25 unique systems. Only three cultivars are grown on M.9 at a density of 4400 trees per hectare, while the remaining two cultivars are grown on M.9 at a reduced density of 2666 trees per hectare. Additional assumptions governing each of the 25 systems are outlined in Table 8.1. Establishment costs, maximum prices and harvest dates are included in the table along with assumptions about trunk cross-sectional area, (TCSA), density and T_f values from previous chapters.

The parameters μ and δ determine growth in the trunk cross-sectional area so that systems growing on M.9 achieve their maximum TCSA relatively early and those growing on Northern Spy achieve maximum TCSA at a relatively late age. The parameter T_f shows the amount of light that is *not* intercepted by the tree and thus reflects tree age, shape and orchard density. It would be common for large, widely spaced trees to have high values of T_f hence a large amount of light is 'wasted'. This is the case for cultivars growing on Northern Spy where values of T_f when fully grown are 0.52. In this case, the trees only intercept 48 per cent of the light that falls on the orchard. The value of T_f for cultivars growing on M.9 at a density of 4400 trees per hectare was originally cited as 0.59 in Table 5.1. This value was calculated from light interception data measured when the trees in the system were two years old. As discussed in Chapter 6, the value of T_f for this system is expected to fall to 0.3 at maturity and is the value adopted for simulation of these systems. This value was also adopted for cultivars growing on M.9 at a density of 2666 trees per hectare.

While each rootstock/density combination has identical μ, δ and T_f parameters, differing values of maximum price, establishment costs and harvest date ensure each cultivar/rootstock/density combination is unique. Establishment costs vary according to price of the tree purchased from the nursery and any costs of trellising or support. Granny

Smith and Red Delicious are assumed to cost A$6.25 per tree and the remaining varieties are assumed to cost A$8.25 due to Plant Variety Right agreements. Highest establishment costs accrue to Pink Lady and Fuji cultivars growing on M.9 at a density of 4400 trees per hectare, trained to a V-trellis (A$52,222 per hectare). The lowest establishment costs accrue in the lowest density systems, for Granny Smith and Red Delicious growing on Northern Spy at 280 trees per hectare (A$3,007 per hectare). The small number of trees planted in this system need no support or training structures, hence the low cost of establishing plantings of this type.

The harvest date differs for each of the five varieties grown on a particular rootstock. The Gala cultivar is the first to be harvested, on 9 February, and Pink Lady is harvested latest, on 29 April. The difference in length of growing season is around 80 days.

Table 8.1: System design and assumptions

Root-stock	**Cultivar**	μ	δ	T_f	**EC (A$/ha)**	**Maximum price ($/kg)**	**Density (trees/ha)**	**Harvest date**
M.9								
	Granny Smith	1.87	0.89	0.30	43,420	1.33	4400	23 Apr
	Pink Lady	1.87	0.89	0.30	52,222	1.67	4400	29 Apr
	Fuji	1.87	0.89	0.30	52,222	1.67	4400	5 Apr
M.9								
	Red Delicious	2.29	0.95	0.30	45,365	1.33	2666	6 Mar
	Gala	2.29	0.95	0.30	50,697	2.00	2666	9 Feb
M.26								
	Granny Smith	1.20	0.29	0.37	24,220	1.33	1666	23 Apr
	Red Delicious	1.20	0.29	0.37	24,220	1.33	1666	6 Mar
	Pink Lady	1.20	0.29	0.37	27,552	1.67	1666	29 Apr
	Fuji	1.20	0.29	0.37	27,552	1.67	1666	5 Apr
	Gala	1.20	0.29	0.37	27,552	2.00	1666	9 Feb
MM.104								
	Granny Smith	1.32	0.30	0.35	7,151	1.33	800	23 Apr
	Red Delicious	1.32	0.30	0.35	7,151	1.33	800	6 Mar
	Pink Lady	1.32	0.30	0.35	8,751	1.67	800	29 Apr
	Fuji	1.32	0.30	0.35	8,751	1.67	800	5 Apr
	Gala	1.32	0.30	0.35	8,751	2.00	800	9 Feb
MM.106								
	Granny Smith	1.00	0.22	0.31	8,770	1.33	1000	23 Apr
	Red Delicious	1.00	0.22	0.31	8,770	1.33	1000	6 Mar
	Pink Lady	1.00	0.22	0.31	10,770	1.67	1000	29 Apr
	Fuji	1.00	0.22	0.31	10,770	1.67	1000	5 Apr
	Gala	1.00	0.22	0.31	10,770	2.00	1000	9 Feb
Northern Spy								
	Granny Smith	0.98	0.20	0.52	3,007	1.33	280	23 Apr
	Red Delicious	0.98	0.20	0.52	3,007	1.33	280	6 Mar
	Pink Lady	0.98	0.20	0.52	3,561	1.67	280	29 Apr
	Fuji	0.98	0.20	0.52	3,561	1.67	280	5 Apr
	Gala	0.98	0.20	0.52	3,561	2.00	280	9 Feb

Annual density-related costs for each system are given in Table B.1 of Appendix B. Density-related costs vary according to the disease resistance status of each cultivar and rootstock. Since Fuji apples are resistant to apple scab their chemical costs are reduced compared to other cultivars. Resistance of MM.106 and Northern Spy rootstocks to woolly apple aphid is also taken into consideration in cost calculations. Bin harvest costs are assumed to be A$23.17 per 400 kg and the discount rate is six per cent.

Initial values of state variables and reserve carbohydrates as well as fruit load information were given in Table 7.1.

8.2 Price Determination

Maximum prices for each cultivar are reported in Table 8.1. The maximum prices were derived from the daily Flemington Market report, compiled by NSW Agriculture and reported on the World Wide Web (www.agric.nsw.gov.au/Hort/Fmrs/Fmrs_report/fruit.htm). Prices were for trading on 23 July 1999. This 'snapshot' of prices is taken from the middle of the 1999 selling season and it is assumed prices are for fruit harvested during Summer and Autumn 1999.[1]

The maximum prices displayed in Table 8.1 were used with price-count relationships determined in Chapter 5 using price data from Batlow Fruit Co-operative. To reiterate, the relationships between count and price were:

$$P_t \begin{cases} P_{75} & \text{if } count_t \leq 75 \\ max\ price & \text{if } 75 < count_t < 105 \\ -0.2448.count & \text{if } count \geq 105 \end{cases}$$

The relativities determined from the Batlow data are maintained for prices and counts in all systems being simulated. The maximum prices of Table 8.1 were used to give the price lines in Figure 8.1. Differences in maximum price cause the price line to rise or fall vertically. Gala apples receive the highest price per carton (A$36) and lowest prices are received by Granny Smith and Red Delicious apples (A$24 per carton).

1 It should be noted that the maximum price for Granny Smith apples used to determine price-count relationships in Chapter 5 and NPV in Chapter 7 was A$43.00 per carton. This price was taken from a sale during January 1999 at a time of relative apple scarcity, hence its high value. The prices used in the current analysis for Granny Smith (A$24.00 per carton) and other varieties are more reflective of average seasonal prices.

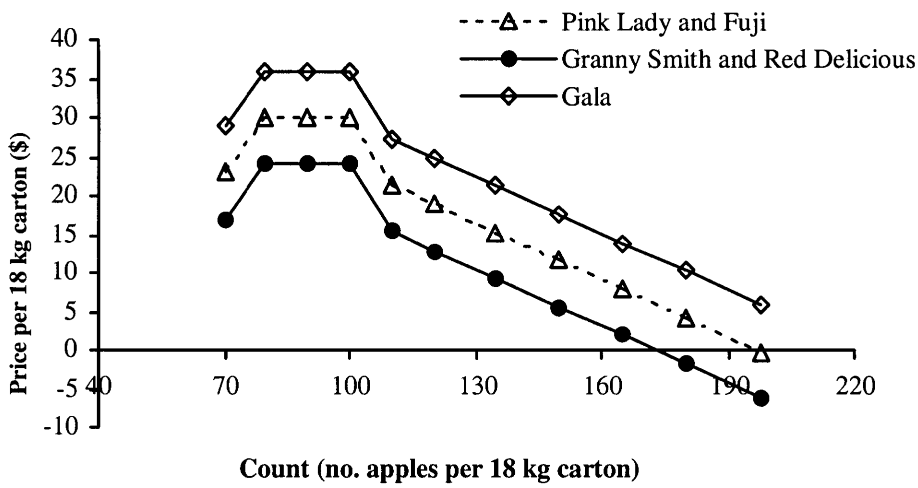

Figure 8.1: Three price-count relationships adopted for Pink Lady and Fuji; Granny Smith and Red Delicious; and Gala apples

8.3 Model Implementation and Solution Technique

Various solution techniques available to optimise the dynamic bioeconomic model were discussed in Chapter 7. In the optimal thinning simulation undertaken in Chapter 7, it was shown that a combination of GA and NLP decreases the possibility of convergence to a local maximum as may occur in traditional NLP models. Despite this, it was decided that NLP would be used as the solution technique in the simulation of each orchard system, given the optimisation application is somewhat different in this chapter.

Rather than maximise NPV for each system by choosing an optimal thinning level in each year of a 15-year planning horizon as was the case in Chapter 7, NPV is maximised subject to four optimal thinning levels. These thinning levels are those that apply in the first three years of fruiting, and a thinning level that applies during and beyond the fourth year of fruiting. The reason for selecting only four optimal thinning values stems from a finding in Chapter 7 that optimal thinning trajectories varied in the first four years of fruiting but remain relatively stable thereafter as illustrated in Figure 7.4. This reduces the dimensionality of the decision problem and decreased the time required to obtain a solution.

In order to guard against convergence to a local maximum by the NLP, optimal values were re-run as starting values for each system until no improvement in NPV was evident.

8.4 Results and Discussion

Results for maximal NPV, cumulative yield and stabilised thinning level for the systems analysed are reported in Table 8.2. Results for annual yield, average price per kilogram and annual profit are reported in Tables C.1 to C.6 of Appendix C.

With the exception of Northern Spy systems, cumulative yields followed the pattern of tree size. Highest cumulative yields for a given cultivar resulted from cultivars grown on MM.106, followed by MM.104, M.26 and M.9 at 2666 trees per hectare with the lowest cumulative yields from trees grown on M.9 at 4400 trees per hectare, the smallest of the trees. Contrary to initial expectations, the profit maximising thinning strategy resulted in cultivars grown on Northern Spy producing no fruit. The reason for this appears to be the sensitivity of state variables to T_f, especially at values greater than 0.5 as discussed in Chapter 6.

In general, the ranking of cumulative yields from highest to lowest for cultivars on a given rootstock appears to mirror harvest date, with late picked varieties (Granny Smith and Pink Lady) having the highest yields, and the early maturing variety (Gala) having the lowest cumulative yields. The Granny Smith and Pink Lady cultivars are picked within six days of each other, hence the closeness in yields in those systems where each is grown. Cumulative yields of Gala are not always the lowest, with Red Delicious producing lower cumulative yields when both cultivars are grown on M.26. This ranking change may be attributable to the model solution converging to a local rather than a global maximum despite attempts to guard against this.

The maximum NPV from all systems is obtained from Pink Lady on MM.106 at a density of 1000 trees per hectare (A$825,000) followed by Gala on MM.106 (A$765,600) and Fuji on MM.106 (A$756,600) (Table 8.2). A combination of high yields for these systems and high prices for these apple varieties produces this result. It is interesting to note that the next highest NPV values are from Pink Lady on M9 (A$728,300) and Fuji on M.9 (A$688,700) at a density of 4400 trees per hectare. These two systems also have the highest establishment costs but it appears the low cost of annual production per tree and the large number of trees per hectare counter this and result in the high profitability of these systems. Apart from systems on Northern Spy, where NPV is negative, the system with the lowest NPV is Red Delicious on MM.104 (A$295,800) while other cultivars on this rootstock also have relatively low values of NPV.

Table 8.2: Results for cumulative yield over 15 years, NPV and thinning for each orchard system

Rootstock	Cultivar	Cumulative yield (kg/tree)	NPV (A$'000/ha)	Thinning rate years 4 to 15
M.9[a]				
	Granny Smith	176	564.2	0.57
	Pink Lady	177	728.3	0.58
	Fuji	172	688.7	0.57
M.9[b]				
	Red Delicious	210	385.8	0.46
	Gala	198	529.1	0.44
M.26				
	Granny Smith	468	449.7	0.23
	Red Delicious	375	346.3	0.18
	Pink Lady	466	614.8	0.22
	Fuji	444	582.7	0.21
	Gala	441	470.7	0.28
MM.104				
	Granny Smith	734	397.9	0.28
	Red Delicious	625	310.1	0.23
	Pink Lady	772	489.4	0.31
	Fuji	726	477.2	0.28
	Gala	570	417.8	0.21
MM.106				
	Granny Smith	970	625.7	0.48
	Red Delicious	830	546.1	0.37
	Pink Lady	968	825.7	0.48
	Fuji	945	756.6	0.46
	Gala	746	765.6	0.32
Northern Spy				
	Granny Smith	0	–23,884	0
	Red Delicious	0	–23,884	0
	Pink Lady	0	–24,438	0
	Fuji	0	–22,581	0
	Gala	0	–24,438	0

a: At 4400 trees per hectare.
b: At 2666 trees per hectare.

In general, within a set of cultivars growing on a particular rootstock, the ranking of NPV from highest to lowest follows the ordering Pink Lady (1), Fuji (2), Gala (3), Granny Smith (4) and Red Delicious (5) (Table 8.2). This ranking is the result of a combination of fruit yield per tree and price per kilogram, rather than one single factor.

Annual profit for all systems are reported in Tables C.1 to C.6 of Appendix C. In general, discounted profit is negative in the first year of growth and becomes positive thereafter as fruit is produced on the trees. This is not the case for cultivars on Northern Spy where the value of discounted profit reflects establishment costs in year one, and annual production costs per hectare in the remaining years.

The optimal thinning level for year four of fruiting and beyond is reported in Table 8.2 and the remaining optimal thinning levels are reported in Table D.1 of Appendix D. While no clear pattern of thinning across systems emerges, the level of thinning in year four and beyond appears to be related to length of growing season and, thus, influences the cumulative fruit yield for a given cultivar. Optimal thinning trajectories allow more fruit to remain on cultivars with long growing seasons and less to remain on those trees with short growing seasons. For example, Pink Lady has the longest growing season and Gala the shortest. When these two cultivars are grown on MM.104, 31 per cent of Pink Lady apples and 21 per cent of Gala apples remain on the tree in year four and beyond, translating into the highest and lowest cumulative yield (772 kg and 570 kg) respectively, for cultivars on this rootstock.

The optimal thinning trajectory results in fruit prices that maximise NPV for each system. Fruit prices for each year of fruiting are given in Tables C.1 to C.6 of Appendix C. In general, for cultivars growing on M.9, the optimal thinning trajectory results in maximum fruit price per kilogram achieved in each year of fruiting. For the remaining rootstocks (excluding Northern Spy) maximum price per kilogram is achieved around year seven and remains at this level in the following years. Strangely, maximum price is never achieved for Gala on M.26. Despite repeated runs of the NLP it appears that a local maximum is achieved in this case. Cultivars grown on Northern Spy do not produce any fruit in the profit maximising runs, hence no price is reported.

In conclusion, it is important to emphasise that results listed in Table 8.2, Appendix C and Appendix D are the result of particular assumptions governing tree growth, system design, input price and output price and are therefore likely to differ as these assumptions change.