WHOLE FARM HARVESTING STRATEGY OPTIMISATION USING THE CANEGRO MODEL: A CASE STUDY FOR IRRIGATED AND RAINFED SUGARCANE

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Abstract

There are two conflicting trends to be considered when optimising crop cycles on a farm. While yield and quality increase as harvest age increases, longer crop cycles reduce the total annual area harvested, potentially reducing the farm's total production. Optimisation of crop cycles is a complex problem, which has to account for the dynamic impact of a multitude of agroclimatic and economic factors. The aim of this study was to demonstrate the use of the CANEGRO model and strategy analysis techniques to identify optimal harvesting strategies for two cases. Seven practical harvesting strategies were simulated for a 27 year period. Annual gross margins were calculated and different criteria of maximum profit and minimum risk applied to identify optimal strategies. Results indicate that, for the irrigated Tala valley scenario, maximum profits would be achieved when 60% of the total area under cane was harvested per annum. The optimal strategy identified for the rainfed Tongaat scenario was to harvest 52.9% per annum. This recommendation excludes the effect of the Eldana stalk borer. A sensitivity analysis showed that the recommendations at Tala valley were relatively stable and could absorb normal fluctuations in harvesting costs and the RV price. It was concluded that the methodology developed here is suitable for optimising harvest strategies and could be applied for other scenarios in the SA sugar industry.

Keywords: harvest age, optimisation, crop model, gross margin, strategy analysis, crop cycle

Introduction

There are two conflicting trends to be considered when optimising crop cycles on a farm. While yield and quality increase as harvest age increases, longer crop cycles reduce the total annual area harvested, potentially reducing the farm's total production. Sugarcane crop production systems are complex with the need to quantify the impacts of many influencing factors. A set of crop cycles, also known as a harvesting strategy, should be planned to optimally exploit a farm's soil and climatic resources and to maximise its annual profit, while minimising risk. Harvesting strategies also need to be practical, allowing for a consistent delivery rate through out the milling season as well as a sustainable plough-out, fallow and re-establishment programme.

Optimal strategies should also be able to tolerate climate variations and price and cost fluctuations. These considerations are especially important since the establishment of a sustainable harvesting strategy on a farm scale could take several years.

Hellmann (1988) assessed harvesting strategies in the Midlands region using a simple linear model based on field production and rainfall data. The criteria for strategy selection were (1) the highest mean annual cane yield and (2) a minimum annual cane yield of more than 40 $t.ha^{-1}$. Hellmann (1988) pointed out that sucrose yield would be a more suitable criterion than cane yield. He also pointed out that results were site specific and that variability in the base data due to variety and soils complicated the interpretation of results.

Crop models, such as the CANEGRO model (Inman-Bamber, 1991) could be suitable tools to assist with this complex task of optimisation. Using the CANEGRO model could overcome some of the limitations identified in the approach of Hellmann (1988). Models capture crop response to climate, soils and management. Inman-Bamber (1995) demonstrated this by deriving radiation and water limited yield benchmarks for sugarcane in South Africa using the CANEGRO model and long term climate data. Simulations based on long-term weather data can also be used to determine the risk associated with different strategies (Thornton and Wilkens, 1998).

Physical crop yield from models can be used to calculate profit for a given production strategy. Profit data could then be analysed to identify the optimal strategy. Thornton and Wilkens (1998) pointed out that strategy analysis could provide useful information concerning the suitability of particular strategies. Different strategy analysis techniques, such as the mean-variance, stochastic dominance and mean-gini methods are available to identify optimal strategies (Tsuji *et al*., 1994). Examples of studies using model based strategy analysis range from the selection of optimum livestock immunisation strategies (Nyangito *et al.,* 1996) to investigating different ways to exploit agricultural markets (Herndon *et al.,* 1999).

Sensitivity analysis can be used to test the stability of the most preferred strategy. The method is based on changing key variables and then assessing the impact on the outcome. For example, Nyangito *et al.* (1996) performed sensitivity analysis based on changing input costs and reported the percentage change required in the input variable before the strategy recommendation would change.

The aim of this study was to assess and demonstrate the applicability of using the CANEGRO model and strategy analysis techniques to optimise harvesting strategies for two case studies in the SA sugar industry. Specific objectives were:

- to calculate long-term yield and gross margin for different harvesting strategies,
- to identify the optimal strategy by considering different criteria,
- and to determine the stability of the optimal strategy recommendation under different price/cost scenarios.

The study focused on long-term strategy implementation and excluded additional potential benefits due to tactical response farming, as highlighted in a study by Stewart (1991).

Method

The CANEGRO model

The CANEGRO model (Inman-Bamber, 1991) simulates the response of the NCo376 variety to agroclimatic conditions. It simulates processes of water movement, like runoff, gravitational flow and root water uptake in a multi-layered soil profile. It also simulates canopy development, which is used to drive the energy balance of the crop by intercepting radiation for photosynthesis. Biomass is dynamically distributed among different components of the plant, including stalk sucrose, based on the crop's age, level of water stress and temperature. A preliminary version (ver 5.1, April 2002) of the model described by Singels and Bezuidenhout (2002) (ver 6.1, May 2002) was used. These two versions have minor differences with respect to biomass partitioning that will have negligible impact on the results presented here. The model does not differentiate between non-sucrose and fibre concentrations in the stalk. Several other factors are not simulated by the model, such as the effects of pests and diseases, weeds, flowering, nutritional deficiencies and ratoon yield decline. The model version described by Singels and Bezuidenhout (2002) does also not include the effect of lodging. In an optimisation exercise it is important to include factors that could limit yield of high yielding crops. Hence it was decided to include a lodging algorithm.

The lodging algorithm calculates an incremental lodging fraction based on water saturation in the soil, the occurrence of strong winds (daily wind run > 200 km.d^{-1}) and the weight of the crop (aerial mass > 220 t.ha^{-1}). Radiation use efficiency (RUE) for the lodged fraction of the crop is reduced by 28% based on Singh *et al.* (1999). The model was validated against data from a growth analysis experiment at Pongola where lodging occurred (Rostron, 1974). Model predictions of stalk dry mass and sucrose yield were more accurate with, than without the lodging algorithm.

The CANEGRO model has been validated for a wide range of agroclimatic conditions and generally simulates cane yield and sucrose yield satisfactory with root mean square errors of 14 t.ha^{-1} and 2.22 t.ha^{-1} respectively (unpublished data). However, no validation data were available for the Midlands region and few data were from crops older than 15 months. Data (832 observations) from the SASEX released variety evaluation programme (RVT) (Redshaw, 1999) from nine rainfed sites in the Midlands and Lower South Coast regions were used to conduct a qualitative validation check. This was done by comparing the 99% confidence boundaries of measured and simulated yield as a function of crop age. The data were not suitable for conventional validation because the experiments were not designed for that purpose.

No management factor was used to reduce model yields to practical attainable yields. This decision was based on preliminary analysis that revealed that using a management factor of 80% had no influence on the identification of optimal strategies.

Simulation setup

Seven practical harvesting strategies (Table 1) were considered for irrigated crops in Tala valley in the Midlands (29°49 'S, 30°28 'E, elev. 692 m) and for rainfed crops at Tongaat on the North coast (29°34 'S, 31°08 'E, elev. 72 m). The Tala valley scenario was chosen following an independent investigation into agronomic efficiency of sugarcane production for growers in this area. It was felt that a rainfed, coastal site would compliment the Tala valley scenario well. Tongaat was selected due to the quality and length of weather data records. At present the recommendations at Tala valley and Tongaat are to annually harvest 65% - 75% and 95% of the total area under cane respectively.

Simulated harvesting strategies were designed to allow for one harvest in each month of the milling season (see Table 1). If implemented on a farm scale, this would ensure a reasonably rateable cane supply throughout the milling season. Crops harvested in April were always ploughed out, left fallow and replanted in October. Table 1 summarises the different harvesting strategies in more detail.

Table 1. Details of the seven harvesting strategies evaluated. Crop age and ratoon stage in brackets (ranging from 'P' for plant crops to 'R8' for 8th ratoon) are given.

Strategy No.	1	2	3	4	5	6	7
April	23(R8)	22(R8)	21(R8)	20(R8)	23(R8)	22(R8)	17(R8)
May	23(R7)	22(R2)	21(R1)	20(R3)	19(R7)	18(R3)	17(R4)
June	23(R6)	22(R7)	21(R4)	20(R5)	19(R2)	18(R7)	20(P)
July	23(R5)	22(R1)	21(R7)	21(P)	19(R5)	21(P)	14(R5)
August	23(R4)	22(R6)	22(P)	21(R7)	22(P)	15(R4)	14(R1)
September	23(R3)	23(P)	22(R3)	21(R2)	15(R3)	14(R1)	14(R6)
October	23(R2)	23(R5)	22(R6)	17(R4)	15(R6)	14(R5)	14(R2)
November	23(R1)	23(R4)	18(R2)	17(R6)	15(R1)	14(R2)	14(R7)
December	26(P)	19(R3)	18(R5)	17(R1)	15(R4)	14(R6)	14(R3)
Average age at harvest (months)	23.3	22.0	20.7	19.3	18.0	16.7	15.3
Area harvested (%/an)	50.0	52.9	56.3	60.0	64.3	69.2	75.0
Area replanted (%/an)	5.5	5.8	6.3	6.7	7.1	7.7	8.3
Years to complete cycle	18	17	16	15	14	13	12

Daily rainfall records from Tala valley were combined with temperature, wind and radiation data from a nearby station at Powers Court (29°58' S, 30°38' E, elev. 631 m). These two sites are 23km apart and were assumed to have similar climatic conditions with the exception of rainfall. Data for the period from 1968 to 1995 from the combined Tala valley/Powerscourt set and from the Tongaat climate station were more than 95% complete. Rainfall records were 100% complete. Long-term monthly mean values were assumed in the isolated cases where temperature and solar radiation data were missing.

CANEGRO simulations were carried out for both sites for each of the seven harvesting strategies (Table 1). A plant crop and all eight ratoon crops were simulated in each year, therefore allowing for nine crops (April to December) to be harvested in each season. Plant crops were assumed to emerge after 21 days, while ratoon crops emerged immediately after the previous crop was harvested. A soil water balance was maintained over consecutive ratoons. One soil description with a total water holding capacity (TAM) of 180 mm was used for all simulations. The soil is described in Table 2.

Table 2. The soil description used to simulate all the crops in this study.

Layer number	Layer thickness (m)	Plant extractable water limits ($\text{mm}^3.\text{mm}^{-3}$)		Saturation level ($\text{mm}^3.\text{mm}^{-3}$)	Relative root distribution
		Lower limit	Drained upper limit		
1	0.05	0.101	0.261	0.368	1.00
2	0.12	0.101	0.261	0.368	0.82
3	0.15	0.101	0.261	0.368	0.64
4	0.15	0.160	0.282	0.371	0.47
5	0.15	0.160	0.282	0.371	0.35
6	0.20	0.151	0.304	0.399	0.22
7	0.20	0.151	0.304	0.399	0.12
8	0.20	0.151	0.304	0.399	0.07

Rainfed crops were simulated for Tongaat and irrigated crops for Tala valley. In order to simulate a realistic irrigated scenario, a long-term mean water balance at Tala valley was used to schedule 15 fixed irrigation events over the period of one year (see Table 3). Each crop received 100 mm of effective irrigation at the start and then 50 mm according to the schedule in Table 3. Irrigation on all crops was terminated 86 days before harvest based on drying off recommendations from Donaldson and Bezuidenhout (2000). The irrigation schedule was maintained irrespective of rainfall and resulted in approximately 750 mm effective irrigation per annum.

Table 3. Dates on which 50 mm effective irrigation was applied at Tala valley.

Month	Date	Total irrigation per month (mm)
January	25th	50
March	7th	50
April	13th	50
May	3rd, 25th	100
June	13th	50
July	2nd, 18th	100
August	3rd, 19th	100
September	6th, 23rd	100
November	5th	50
December	3rd, 30th	100
Total	15 events	750 mm

Economics

Production costs relative to the 2000 milling season were used. These are shown in Table 4.

Table 4. Details of the cost scenario assumed for this study.

Variable name	Unit	Description	Value
Ratoon costs	R.ha^{-1}	Total for one hectare	2754.70
	R.ha^{-1}	Labour	242.00
	R.ha^{-1}	Fertiliser	1994.30
	R.ha^{-1}	Herbicides	357.60
	R.ha^{-1}	Fertiliser application	67.00
	R.ha^{-1}	Herbicide application	93.80
Replant costs	R.ha^{-1}	Total for one hectare	6910.50
	R.ha^{-1}	Land preparation	1360.00
	R.ha^{-1}	Labour	770.00
	R.ha^{-1}	Fertiliser	1855.10
	R.ha^{-1}	Herbicides	597.60
	R.ha^{-1}	Seed cane	2100.00
	R.ha^{-1}	Fertiliser application	134.00
	R.ha^{-1}	Herbicide application	93.80
Harvesting costs	R.t^{-1}	Total for one ton of cane	41.93
	R.t^{-1}	Cut and windrow	4.80
	R.t^{-1}	Grab loading	4.74
	R.t^{-1}	Infield haulage	7.47
	R.t^{-1}	Transhipment	2.92
	R.t^{-1}	Haulage to mill (20 km)	22.00
Net irrigation rate (Net_Irrig_Rate)	R.mm^{-1}.ha^{-1}	The operational cost to apply effective irrigation: Cost of water: R140.ha^{-1}.an^{-1} Power cost: R0.23.kWh^{-1} Pumping height: 50m Stand time: 12h Gross Irrigation: 66mm.ha^{-1} Irrigation Efficiency: 75% Net Irrigation: 50mm.ha^{-1}	0.92

Annual farm gross margin per area under cane (R.ha^{-1}.an^{-1}) was calculated according to eq. 1

$$\text{Gross\_Margin} = \text{Income} - \text{Replant\_Cost} - \text{Ratoon\_Cost} - \text{Harv\_Cost} - \text{Irr\_Cost} \tag{1}$$

where Replant_Cost, Ratoon_Cost and Harv_Cost are the annual costs per total area under cane (R.ha^{-1}.an^{-1}) associated with replanting, ratooning and harvesting respectively.

Annual income per total area under cane (R.ha^{-1}.an^{-1}) was calculated according to eq. 2. CANEGRO does not differentiate between non-sucrose and fibre, making the calculation of relative value (RV) (Murray, 2000) impossible. A sucrose price (Suc_Price) of R990.99 per ton was used after assuming a fixed factor of 0.90 between the 2000 RV price (R1100 per ton) and the sucrose price.

$$\text{Income} = \text{Suc\_Price} \times \text{Suc\_Prod} \tag{2}$$

where Suc_Prod is the annual simulated sucrose production per total area under cane (t.ha^{-1}.an^{-1}).

The annual cost of irrigation per area under cane, Irr_Cost ($R.ha^{-1}.an^{-1}$, eq. 3), was calculated from the strategy's long-term average annual irrigation amount (Avg_Total_Irrig, $mm.an^{-1}$).

$$\mathrm{Irr\_Cost} = \mathrm{Avg\_Total\_Irrig} \times \mathrm{Avg\_Crop\_Age} / 365 \times \mathrm{Net\_Irrig\_Rate} \qquad (3)$$

where Avg_Crop_Age is the average crop age at harvest (days) and Net_Irrig_Rate is the cost associated with applying 1 mm of effective irrigation per area under cane (see Table 4).

Variables in eqs. 1, 2 and 3 account for the fact that fractions of the farm is harvested and replanted annually (see Table 1), while Table 4 reflects the costs associated per area harvested or replanted.

Analysis of model output

Gross margin results from different harvesting strategies were evaluated according to the criteria of long-term median and mean. Strategies were also ranked according to profitability within a season (following Nyangito *et al*., 1996), and each strategy's mean rank over seasons was calculated. Standard deviation was used as a secondary criterion to evaluate the risk associated with each strategy.

The sensitivity of the optimal strategy to changes in the RV price and harvesting costs, driven by factors such as the petrol price and distance to the mill, was evaluated. This was done by determining the optimal strategies under different permutations of harvesting costs and RV prices.

Results

CANEGRO validation

Confidence intervals of observed and simulated sucrose yields compared well (Figure 1). It is noteworthy that the climatic potentials (top boundaries of confidence intervals) were reasonably similar for crops exceeding 18 months in age. The fact that simulated and observed climatic potentials of crops younger than 18 months did not coincide could be explained by the generally warmer and more favourable growing conditions at Tongaat and Tala valley than that of the cooler experimental sites.

This qualitative validation revealed no serious, inexplicable deviations between the observed and simulated data. It was therefore concluded that the CANEGRO model could be used with a fair amount of confidence to simulate growth response for crops exceeding 15 months in age.

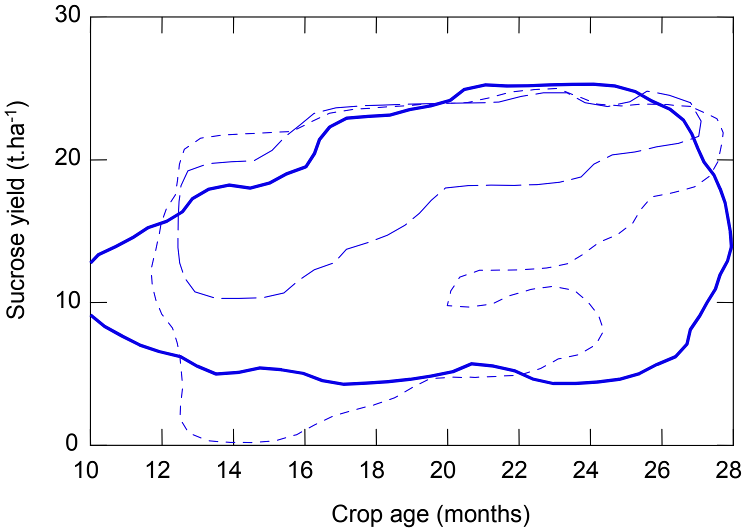

Figure 1. The 99% confidence intervals for observed (solid) and simulated sucrose yields at Tala valley (long dashed) and Tongaat (short dashed).

Strategy analysis

Figures 2a, 2b and 2c illustrate probability distributions for cane yield, sucrose content and gross margin for different harvesting strategies at Tala valley and Tongaat. Table 5 summarises the median, mean, standard deviation and mean intra-seasonal rank for gross margin for each strategy at both sites. Generally there was less inter-seasonal variation at Tala valley than Tongaat and variation also decreased as crops were harvested at older ages. Cane yield and sucrose content increased linearly with a decrease in percentage area harvested.

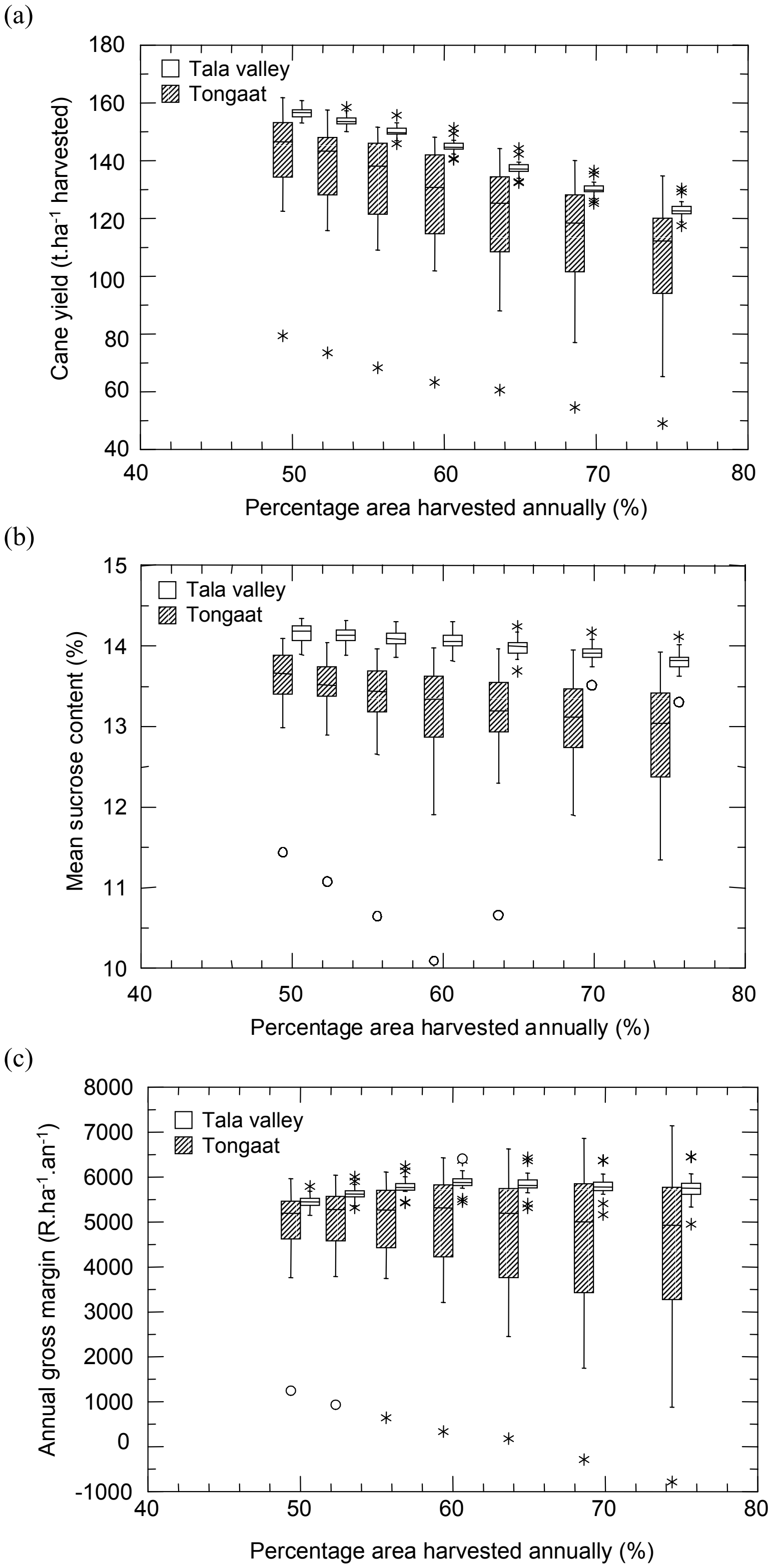

Figure 2(a,b,c). Box and whisker plots for cane yield (a), sucrose content (b) and annual gross margin (c). Rectangles depict the 25th to 75th percentile intervals. Solid lines depict the 10th to 90th percentile intervals. Other marks represent outliers (*) and far outliers (°).

Table 5. Median, mean and standard deviation (StdDev) and mean intra-seasonal rank for gross margin for different harvesting strategies at Tala valley and Tongaat. Underlined values depict the optimal strategy under each criterion.

Area harvested (%/an)	Tala valley (29°49'S, 30°28'E, elev. 692m)				Tongaat (29°34'S, 31°08'E, elev. 72m)			
	Median	Mean	StdDev	Mean rank	Median	Mean	StdDev	Mean rank
	R.ha^{-1}				R.ha^{-1}			
50.0	5450	5446	148	6.923	5194	4971	914	3.692
52.9	5624	5632	150	5.654	5277	4991	1032	3.308
56.3	5766	5792	171	3.615	5269	4957	1158	3.269
60.0	5877	5900	202	1.192	5317	4890	1307	3.615
64.3	5817	5838	228	2.538	5195	4755	1438	4.077
69.2	5780	5798	241	3.577	5000	4611	1666	4.615
75.0	5753	5739	298	4.500	4930	4411	1917	5.423

From these results it is concluded that the 60% harvesting strategy for Tala valley was significantly superior to any other strategy. This corresponds with the findings of Hellmann (1988) who recommended harvesting strategies ranging from 52.9% to 64.3%.

At Tongaat the 52.9%, 56.3% and 60.0% harvesting strategies were similar to each other, but superior to other strategies. The strategies still had different levels of risk and different growers might prefer different strategies depending on their attitude towards risk. The 52.9% harvesting strategy would be recommended for risk-neutral growers as it had the highest mean gross margin and the lowest standard deviation. An investigation into the probability of crop failure (gross margin below R2000/ha) showed that this criterion did not add any discrimination between strategies.

The results for Tongaat conflict with the current practice of harvesting 95% of the total area. The main reason for this deviation is believed to be due to the impact of Eldana stalk borer, which was not simulated.

Sensitivity analysis

Figures 3(a) and 3(b) illustrate the optimal harvesting strategy using maximum mean gross margin as criterion for different RV prices and harvesting costs. It is evident from Fig. 3(a) that for Tala valley the 60% harvesting strategy was identified as the optimal recommendation for a large number of economic scenarios. The same strategy would be optimal if RV price changed with 30% or harvesting costs changed with 100% from current levels (marked with an 'X' in Fig. 3a). The optimal strategy at Tongaat (Fig. 3(b)) changes more readily when the economic scenario changes. The 52.9% harvesting strategy would remain optimal for changes of only 30% in either the RV price or harvesting costs.

Discussion and Conclusions

This paper demonstrated the use of a crop growth model to optimise harvesting strategies. The CANEGRO model with a lodging algorithm was shown to be a suitable tool to investigate the optimisation of harvesting strategies. It is anticipated that the influence of other factors, such as the impact of Eldana, should also be regarded as important in some cases. It is therefore always important to assess the applicability of the model before commencing with simulations.

The analysis indicates for both Tala valley and Tongaat that current practices might be sub-optimal and longer cropping cycles could increase profits. A 60% harvesting strategy at Tala valley was superior to all other strategies. The 52.9%, 56.3% and 60.0% harvesting strategies at Tongaat achieved high gross margins. Based on a neutral attitude towards risk, the 52.9% harvesting strategy is recommended for Tongaat. Due to the model's inability to simulate the impact of Eldana, results for Tongaat are only valid for low Eldana infestation levels.

This technique could be used to estimate the economic impact of Eldana and sub-optimal management practices on the sugar industry and quantify the potential benefit of research to alleviate these problems.

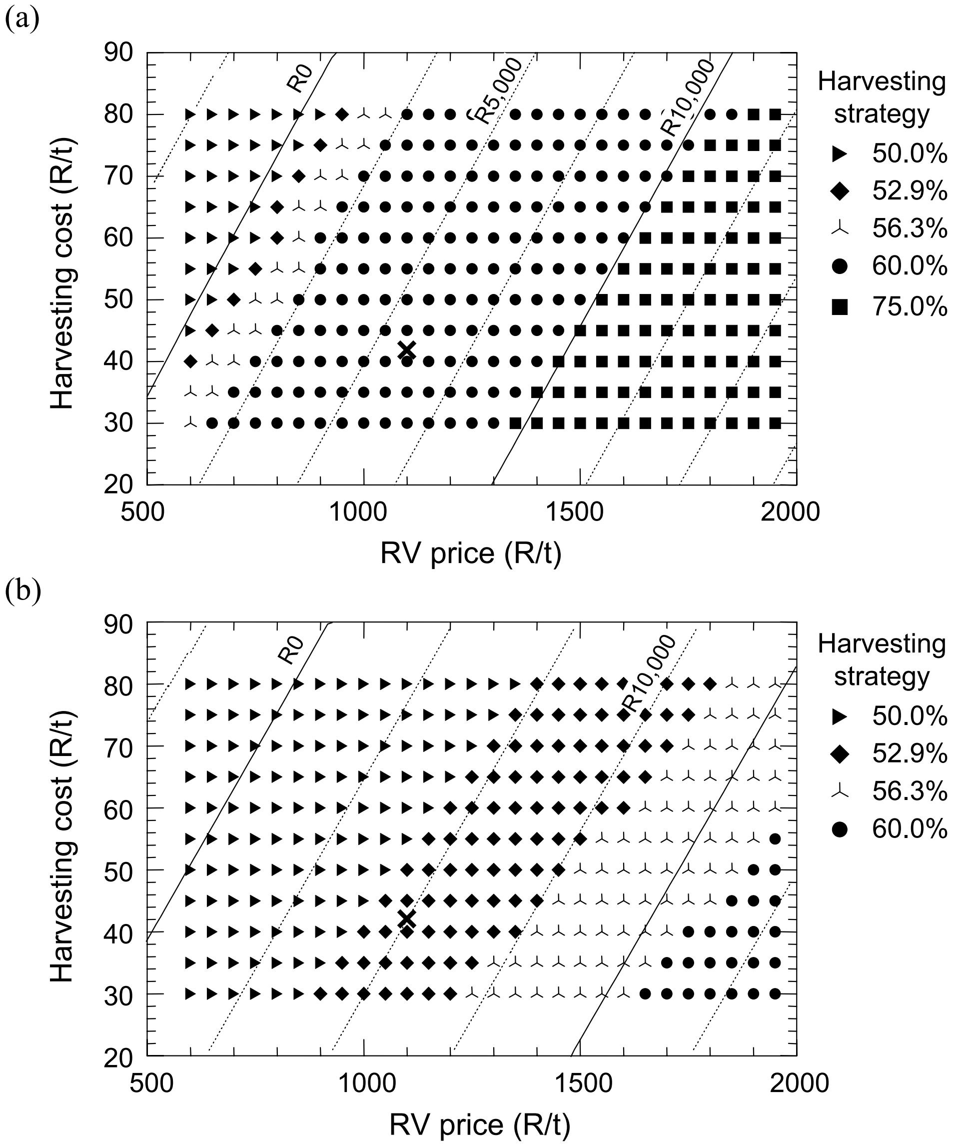

Figure 3. Optimal cropping cycle strategies mapped out over a range of hypothetical RV prices and harvesting costs at Tala valley (a) and Tongaat (b). Contour lines depict the mean gross margin, while the cross (X) shows the position assumed for the 2000 price scenario (Table 3).

The stability of the recommended harvesting strategies were assessed by using sensitivity analysis. The results showed that relatively large fluctuations in the RV price and harvesting costs would not necessarily require changes in harvesting strategies at Tala valley. In both cases the stability of the recommended strategy will increase if the RV price and harvesting cost are well correlated, as can be expected due to the comparable impact by the currency exchange rate.

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