An analysis of sugarcane harvesting options in the Tully mill area using dynamic and linear programming

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Abstract

Sugarcane in a perennial crop harvested annually over a six-month season from June to December. Each crop cycle consists of a plant crop followed by several ratoon crops. Time of harvest influences both commercial cane sugar (CCS) content in the current season and yield in the following season. Legislative requirements force growers to harvest some of their cane during sub-optimal periods and growers have to decide the order in which to harvest blocks when both yield and sugar content that determine block returns are uncertain.

Industry data about yield and (CCS) stored in a MS Access database were used in a dynamic programming analysis of potential harvest sequences. Optimal harvest patterns were identified given industry constraints on cane harvested in several equal time periods during the season.

Keywords: sugarcane; dynamic programming; linear programming; databases; sql

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Introduction

Australian sugarcane is grown as a perennial monoculture that is harvested at approximately annual intervals between June and December. The resultant cane yield (t/ha) is primarily driven by incident radiation and rainfall and the distribution of rainfall within the growing season (Rostron 1972, Inman-Bamber 1994, Muchow *et al.* 1997).

The harvesting operation in a mill area is highly organised and ensures that each grower harvests an approximately equal portion of their crop in four equally spaced periods between June and December. Since the climatic conditions that a crop is exposed to varies across the mill area and with each season, growers must decide which farm paddocks should be harvested early in the season, in the middle of the season, and towards the end of the season. The time when the crop is harvested determines the age of the cane at harvest and influences the yield of the following crop (Lawes *et al.* 2002, McDonald and Wood 2001).

In the Tully mill area in far North Queensland, information about cane yields and the characteristics of the blocks from which it originates is collected and stored digitally as part of the process of purchasing cane from farmers and delivery to the mill. In such a commercial environment, a large number of identifiable factors such as variety, crop class, time of harvest, time of harvest of the previous ratoon crop, farm of origin, and year of harvest influence cane yield (Lawes *et al.* 2002). Descriptive models of sugarcane yield were developed from this database and it was therefore possible to develop a theoretical management strategy to maximise cane yield from the whole farm over four years of the crop cycle, making sure that sufficient cane is harvested during all possible harvest periods to comply with the mill's requirements for cane during the crushing season from June to December. Although complex scheduling strategies have previously been developed by Higgins (1999) to maximise industry income across several geographical regions, a model that optimises the harvesting of cane at the farm level had not been developed. In this study, we have utilised dynamic and linear programming techniques to build input matrices for cane yield and to find the optimum combination of crop harvesting activities that constitute the optimal decision path.

Methods

Data

In the Tully Sugar Mill area, situated in the wet tropics of North Queensland Australia, block productivity data from 1988 to 2000 has been digitally recorded. Information such as month of harvest, month of ratooning (the month of harvest of the previous crop), farm of origin, crop class, variety, cane yield, and CCS (commercial cane sugar content) is available for each block of cane harvested over this period. However, the date of planting at the start of each crop cycle was not recorded so the age of plant cane at harvest was unavailable. Approximately 65,000 block records were available and a detailed description and analysis of these data was presented in Lawes *et al.* (2002). Half of these data (35,219 records) were selected at random using Genstat version 5 release 4.1 to develop the model (input data). Remaining data were used to validate the model, although the validation process is not reported here (validation data).

Model development: statistical analysis

The response of cane yield to the time of harvest in the present and subsequent crops was sought to develop an on farm harvest scheduling model. In this instance the harvesting season was split into four harvest periods, each of approximately 6 weeks duration. Each grower must harvest approximately one quarter of the crop in every one of these periods. Therefore the harvest season was divided into four six-weekly periods, indicative of when the crop is to be harvested. The time of ratooning, which is the time when the crop was harvested in the previous year, was divided into the same four, six-week periods.

The model used to explain cane yield from the input data, where all effects were defined as random, is presented in equation (1):

$$tch_{ijkl} = \mu + year_i + farm_j + tor_k + toh_{kl} + e_{ijkl} \qquad (1)$$

where tch_{ijkl} is the cane yield in tonnes per hectare for the i^{th} year, j^{th} farm of origin, k^{th} time of ratooning and l^{th} time of harvest with in the k^{th} time of ratooning. μ is the overall mean; $year_i$ is the i^{th} year when the crop was harvested; $farm_j$ is the j^{th} farm of origin; tor_k is the k^{th} time of ratooning and toh_{kl} is the effect of time of harvest l within time of ratooning k. and e_{ijkl} is the error for the i^{th} year, j^{th} farm, k^{th} time of ratooning and l^{th} time of harvest with in the k^{th} time of ratooning.The objective of this analysis was to obtain values of cane yield for every possible combination of time of harvest and time of ratooning. The nesting of time of harvest within time of ratooning effectively captures all timing influences on cane yield, including the influence of crop age. The nested model was adopted as the time of ratooning indicates when the new crop started to grow. Therefore the time of harvest effect will be influenced by the time when the crop was ratooned. These effects plus the overall mean were used in the subsequent network analysis.

Model development: optimisation of harvest schedules

In every year, every cane grower is faced with the decision of when to harvest each individual block of cane. This harvesting decision influences the TCH and CCS (which are the important components of monetary return) of the existing crop as well as the TCH of the following crop. The farmer must therefore consider what impact a harvesting decision has on both the current and following sugarcane crop. The two dominant effects, on sugar yield, the time of ratooning (which affects cane yield) and the time of harvest (which affects CCS) were captured in equations 1 and 2.

The sequence of events involved in the whole crop cycle, that is the planting and subsequent harvests of plant cane, first ratoon cane, second ratoon cane, third ratoon cane, ploughing out and fallowing the block can be described in dynamic programming terms as a network problem with a series of nodes (eg Chang and Sullivan 1991). The origin and source of the network, node 1, indicates the point when the crop was planted in the ground and is the beginning of the sequence of events that occur for each block of cane. At each node, there are two options that the grower can exercise: harvest or not harvest. Any pair of nodes are designated r and h and the path connecting the two nodes is identified as a branch(r,h) with a corresponding yield(r,h). The individual nodes represent each year in the crop cycle of a single sugarcane crop (a stage in dynamic programming terms), and each branch(*r,h*) represents a potential time of ratooning(*r*) and time of harvest(*h*) (Figure 1). There are four in each year. The progression from one node to the next along the branch(*r,h*) equates to moving from 1 year to the next in the crop cycle (Figure 1).

With the exception of node 1, every other node indicates that the crop has been harvested and a cane yield results from that action. The branches are directed, where the branch(*r,h*) and therefore yield(*r,h*) is possible, but the branch(*h,r*) and yield(*h,r*) is not. The exception to this rule occurs when cane is harvested in the 3rd ratoon, nodes 14,15,16 or 17. At this point the cane is ploughed out and the block is fallowed. The network is a re-occurring system and returns to the same state at node 1 but no cane yield results from this action.

The potential harvest dates for any block of cane can be represented by the network in figure 1. There are 17 nodes with 52 possible node branches(*r,h*) and corresponding yields(*r,h*). For each block of cane, there are 64 possible paths through the network. The potential total yield from the block, is the sum of all yields(*r,h*) encountered on a particular path, which must consist of 4 branches(*r,h*) and the return loop back to the start of the sequence. The branches(*r,h*), corresponding yields(*r,h*), time of ratooning and time of harvest associated with each branch are presented in table 1.

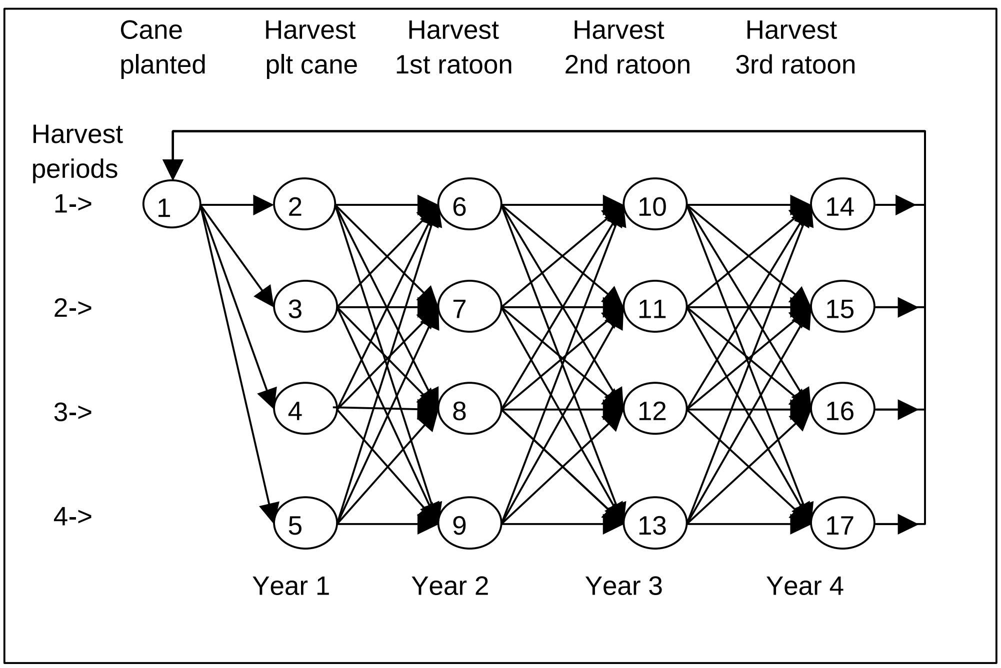

Figure 1. Model describing harvest timing sequences in dynamic programming terms as a network problem with a series of nodes. Nodes are indicated by circles with the node number specified in the circle. The direction of flow and progression from one node to the next is indicated by the arrows.

Table 1. Cane yield associated with each branch of the network for each ratoon time and harvest time.*

Ratoon Time	Harvest Time (t)	branch(*r*,*h*)	yield(*r*,*h*) t/ha
1	1	(1,2), (2,6), (6,10), (10,14)	82
1	2	(1,3), (2,7), (6,11), (10,15)	90
1	3	(1,4), (2,8), (6,12), (10,16)	89
1	4	(1,5), (2,9), (6,13), (10,17)	83
2	1	(3,6), (7,10), (11,14)	82
2	2	(3,7), (7,11), (11,15)	90
2	3	(3,8), (7,12), (11,16)	90
2	4	(3,9), (7,13), (11,17)	89
3	1	(4,6), (8,10), (12,14)	74
3	2	(4,7), (8,11), (12,15)	83
3	3	(4,8), (8,12), (12,16)	85
3	4	(4,9), (8,13), (12,17)	85
4	1	(5,6), (9,10), (13,14)	60
4	2	(5,7), (9,11), (13,15)	68
4	3	(5,8), (9,12), (13,16)	67
4	4	(5,9), (9,13), (13,17)	74
Return to origin		(14,1), (15,1), (16,1), (17,1)	N/a

* These yields are the expected values derived from equation 1.

The objective of establishing a network was to determine all possible harvesting options on a farm. However the network illustrated in figure1 outlines the possible harvesting options for a single block over a five year period. Obviously there are a number of blocks on a farm, and at any one time there is a mix of fallow land, plant cane, first ratoon cane, second ratoon cane and third ratoon cane. A single network can not accommodate the usual mix of ratoons on a typical farm since cane is planted each year. Thus, five networks were used, each of which commences in a different year (Table 2).

Table 2. The relationship between the network origin and the year on the farm. The crop class harvested in each year for the specific network is also indicated.

	Nodes accessed by the respective network in year 1,2,3,4 and 5				
Year	Network 1, node number and ratoon harvested	Network 2, node number and ratoon harvested	Network 3, node number and ratoon harvested	Network 4, node number and ratoon harvested	Network 5, node number and ratoon harvested
1	1 fallow	14,15,16,17 3rd ratoon	10,11,12,13 2nd ratoon	6,7,8,9 1st ratoon	2,3,4,5 plant cane
2	2,3,4,5 plant cane	1 fallow	14,15,16,17 3rd ratoon	10,11,12,13 2nd ratoon	6,7,8,9 1st ratoon
3	6,7,8,9 1st ratoon	2,3,4,5 plant cane	1 fallow	14,15,16,17 3rd ratoon	10,11,12,13 2nd ratoon
4	10,11,12,13 2nd ratoon	6,7,8,9 1st ratoon	2,3,4,5 plant cane	1 fallow	14,15,16,17 3rd ratoon
5	14,15,16,17 3rd ratoon	10,11,12,13 2nd ratoon	6,7,8,9 1st ratoon	2,3,4,5 plant cane	1 fallow

The potential yield from all paths through the five networks was then determined to generate a table that indicates the branch(*r*,*h*) and the yield(*r*,*h*) for each specific year and harvest time. A subset of this table is presented below (Table 3). Each possible path was given a rotation number (*r*1..*r*320).

Table 3 Three of the 320 possible rotations, with a specified rotation number, taken through the network are illustrated. The yield(*r*,*h*) generated from the action of harvesting at the specified node is also given. Harvest times within a year are aligned with their respective nodes. The year of the cycle is also indicated, as is the action that takes place at the node in that year.

				Path and rotation number (r)		
				r1	r2	r3
Year (*y*)	Crop class and action	Harvest time (*t*)	Node	yield(*r*,*h*)	yield(*r*,*h*)	yield(*r*,*h*)
1	Fallow and	1	1			
1	then the crop planted	2				
1	no crop harvested	3				
1		4				
2	plant cane	1	2			
2	crop harvest	2	3	90	90	90
2		3	4			
2		4	5			
3	1st ratoon	1	6			
3	crop harvest	2	7	90	90	
3		3	8			90
3		4	9			
4	2nd ratoon	1	10			
4	crop harvest	2	11	90		83
4		3	12		90	
4		4	13			
5	3rd ratoon	1	14			
5	crop harvest	2	15			
5	land fallowed	3	16			
5		4	17	89	85	89

From table 3 the following notation can be adopted, a rotation (*r*1..*r*320) can be followed that generates a yield(*r*,*h*) in year (*y*1..*y*5) at harvest time (*t*1..*t*4). Each harvest time occurs in every year, therefore any given harvest time in any given year is denoted by *yt*. This table is identified as *C*, cane yield, where the columns (*r*1..*r*320) denote the rotations and the harvest time in a given year is identified by the rows (*yt*), of which there are 20 (five years in the crop cycle and four harvest times in each year).

It was assumed that the farm had a uniform area of fallow, plant cane, first ratoon, second ratoon and third ratoon cane in every year. In this instance we assumed the total farm size was 100 ha and there were 20 ha of each crop class. In any given year 80 ha of land must be harvested and 20 ha left bare under fallow. Twenty hectares must be harvested at each of the four harvest times.

Therefore when a yield(*r*,*h*) is generated at *yt* from rotation *r*, cane has been harvested, and is designated *yt*,*r*. A new table L, the land requirement was also defined. In this case the yield(*r*,*h*) is replaced with a binary identifier at *yt*,*r*. This binary indicator is necessary to identify when cane is harvested in rotation *r*. In this instance growers can only harvest a total of 20 ha at each *yt* and once a rotation has been selected, an alternative must be sought that harvests an area of cane at a different *yt*. The decision variable is therefore how much of each rotation to adopt across the farm, where a_r is the area in hectares to allocated to a rotation (*r*1..*r*320). This is subject to the system constraints that the amount of cane to be harvested at each year at each harvest time (*yt*) is defined in equation 3 as

$$\sum_r L_{ytr} \times a_r \le 20 \qquad (3)$$

Where L_{ytr} is the land requirement at y^{th} year and t^{th} harvest time for the r^{th} rotation, which must be less than the maximum amount of land that can be harvest in the y^{th} year at the t^{th} harvest time. In this case this was set to 20; a_r is the amount of land to assign to the r^{th} rotation (Table 4).

Table 4. A table showing the land requirement at each harvest time and year. The binary identifier is synonymous with the construction of table L, used in equation 4*.

		a1×r1	a2×r2	a3×r3...a_r×r_n	∑a_r×r_n
Year(*y*)	Harvest time(*t*)	yield(*r*,*h*)	yield(*r*,*h*)	yield(*r*,*h*)	Total area to harvest at *yt*
1	1	a1×0	a2×0	a3×0	≤ 20
1	2	a1×0	a2×0	a3×0	≤ 20
1	3	a1×0	a2×0	a3×0	≤ 20
1	4	a1×0	a2×0	a3×0	≤ 20
2	1	a1×0	a2×0	a3×0	≤ 20
2	2	a1×1	a2×1	a3×1	≤ 20
2	3	a1×0	a2×0	a3×0	≤ 20
2	4	a1×0	a2×0	a3×0	≤ 20
3	1	a1×0	a2×0	a3×0	≤ 20
3	2	a1×1	a2×1	a3×0	≤ 20
3	3	a1×0	a2×0	a3×1	≤ 20
3	4	a1×0	a2×0	a3×0	≤ 20
4	1	a1×0	a2×0	a3×0	≤ 20
4	2	a1×1	a2×0	a3×1	≤ 20
4	3	a1×0	a2×1	a3×0	≤ 20
4	4	a1×0	a2×0	a3×0	≤ 20
5	1	a1×0	a2×0	a3×0	≤ 20
5	2	a1×0	a2×0	a3×0	≤ 20
5	3	a1×0	a2×0	a3×0	≤ 20
5	4	a1×1	a2×1	a3×1	≤ 20

*a_r is the area assigned to the r^{th} rotation.

The farmer is interested in maximising cane yield over five years across the entire property. This is summarised in the equation 4, the objective function (z) as

$$z = \max \sum_{yt} C_{ytr} \times a_r \qquad (4)$$

Where z is the objective value, tonnes of cane; C is the cane yield at the y^{th} year and t^{th} harvest time in the r^{th} rotation and a_r is the area in hectares assigned to r^{th} rotation.

Results and discussion

Effect of harvest time on cane yield

The time of ratooning and time of harvest both influenced cane yield, although the time of ratooning (previous harvest) was generally more important than the time of harvest (Figure 2). Crops ratooned in period 4 yielded between 8 and 10 t/ha less than crops ratooned in period 3 for all harvest times. Crops ratooned in period 3 yielded between 7.8 and 8.4 tonnes/ha less than crops ratooned in periods 1 and 2, when the crop was harvested in either period 1, 2 or 3.

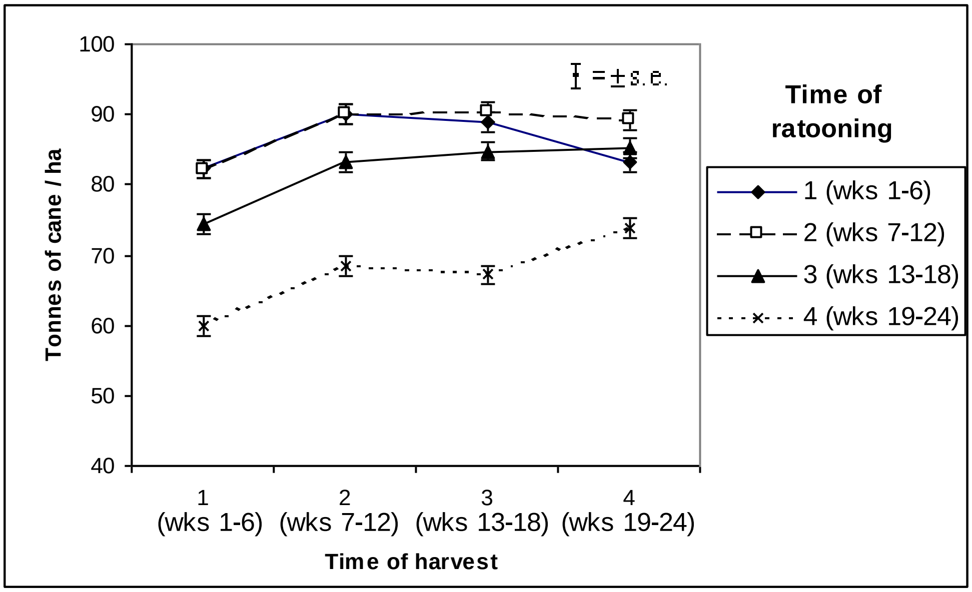

Figure 2. Influence of time of ratooning and time of harvest on cane yield in the Tully district from 1988 to 1999, as estimated using harvest data from 35,000 block productivity records.

Managing the crop over the life of a ratoon

The incorporation of the above effects calculated from the Tully block data into the dynamic programming routine for all combinations of time of ratooning and time of harvest during a four-year sequence generated a wide range in expectations for cane yield from a block of cane over the life of the crop. From the 64 possible harvesting sequences identified by the network, total cane yield ranged from 359 tonnes down to 300 tonnes per ha. This equates to an average cane yield per year of between 90 t/ha and 75 t/ha. An example of a high yielding harvesting sequence and a low yielding sequence are illustrated in table 6. The crop from the high yielding sequence was planted in the first period (approximately June/July), and then harvested in the second period (August/September). In the following year the first ratoon crop was again harvested in the second period at twelve months of age. The second ratoon crop was also harvested in the second period. The third and final ratoon was then harvested in the final period and then ploughed out. In contrast the crop from the low yielding harvest sequence was planted in the 1st period (June/July) and harvested in the 4th period (November) at approximately 17 months of age. In the following year the first ratoon crop was then harvested in the 4th

period. The second and third ratoon crops were again harvested in the 4th period at 12 months of age. Because farmers must harvest an equal portion of cane in each period, the high yielding solution cannot be applied across the whole farm.

Table 6. Tabulation of the ratoon and harvest period and expected cane yield from plant cane to third ratoon for a high yielding harvest sequence and a low yielding harvest sequence.

	High yielding harvest sequence			Low yielding harvest sequence		
	Period of ratooning	Period of harvest	Cane yield t/ha	Period of ratooning	Period of harvest	Cane yield t/ha
Plant cane *	1	2	90	1	4	83
1st ratoon	2	2	90	4	4	74
2nd ratoon	2	2	90	4	4	74
3rd ratoon	2	4	89	4	4	74
Total yield			359			305

* The period of ratooning of plant cane equates to the period when the crop was planted.

When each of the area and time constraints, described in equation 3, were introduced for a rotation that included a year of fallow, plant cane, 1st ratoon, 2nd ratoon and 3rd ratoon, the optimal solution differed from that derived for a single block of cane. Five rotations, out of a possible 320, were utilised, and these five rotations were identical, except for the year that the block was fallowed. The optimal rotation stipulated that a crop was to be fallowed and planted in June. The plant crop would be harvest during the first period (June/July) at approximately 12 months of age and yield 82 t/ha. The first ratoon crop would then be harvest during the 2nd period of the following year (July/August) at 13 to 14 months of age and produce 90 t/ha. The following second ratoon crop was harvested in the third period at 13 to 14 months of age and produced 90 t/ha. The 3rd ratoon was then harvested during the 4th period at 13-14 months of age and yielded 85 t/ha. This is depicted in figure 3 where, for each rotation, the crop class is identified and the period when this class is harvested is also noted. An equal area of each rotation was adopted, so in any given year there is an equal area of plant, 1st ratoon, 2nd ratoon, 3rd ratoon and fallow. In general the time of harvest of the successive ratoon crops was progressively advanced later into the harvesting season until the third ratoon, when the land is plough out and again fallowed (Table 7).

Table 7. The optimal rotation strategy for a 100 ha farm with uniform areas of all crop classes. The time of harvest, crop class and the predicted cane yield for every year for each rotation are identified.

	Crop class, cane yield and time of harvest for optimum rotation.				
Area of rotation	Year 1 ⇒	Year 2 ⇒	Year 3 ⇒	Year 4 ⇒	Year 5
20 ha	Fallow No yield	Plant 82 t/ha 1st Period	1st Ratoon 90 t/ha 2nd Period	2nd Ratoon 90 t/ha 3rd Period	3rd Ratoon 85 t/ha 4th Period
20 ha	Plant 82 t/ha 1st Period	1st Ratoon 90 t/ha 2nd Period	2nd Ratoon 90 t/ha 3rd Period	3rd Ratoon 85 t/ha 4th Period	Fallow No yield
20 ha	1st Ratoon 90 t/ha 2nd Period	2nd Ratoon 90 t/ha 3rd Period	3rd Ratoon 85 t/ha 4th Period	Fallow No yield	Plant 82 t/ha 1st Period
20 ha	2nd Ratoon 90 t/ha 3rd Period	3rd Ratoon 85 t/ha 4th Period	Fallow No yield	Plant 82 t/ha 1st Period	1st Ratoon 90 t/ha 2nd Period
20 ha	3rd Ratoon 85 t/ha 4th Period	Fallow No yield	Plant 82 t/ha 1st Period	1st Ratoon 90 t/ha 2nd Period	2nd Ratoon 90 t/ha 3rd Period

The unusual feature about this cropping and ratooning sequence is the early harvest and consequently low yield for plant cane. Most growers would regard their plant cane as their most important crop and harvest it at the time of peak production (both yield and ccs) although this analysis suggests that a greater level of overall production can be achieved by considering all crops in the sequence, not just the plant cane.

Conclusions

Growers value information on variety performance and use this information to improve production. Like varieties, the time of ratooning has an impact on the yield of the crop and like varieties, growers must decide which blocks to harvest in particular harvesting rounds. Obviously this will be affected by factors such as trafficability under wet conditions, the crop class and maybe whether the block is high yielding or otherwise. There are many reasons for harvesting a block at a given time, and from the evidence presented here, we suggest that growers consider the impact that a late ratooned crop has on the yield of the following crop when deciding which blocks to harvest in each round. Similarly the time of planting and age of the crop at harvest should be considered by researchers and perhaps accommodated in the experimental design of variety selection trials. It is common practice to evaluate the varietal response to a treatment, and it may therefore be worth evaluating the interaction between harvest time and the treatment, as a crop planted or ratooned early is exposed to a different climatic regime to a crop planted or ratooned later in the season and these climatic differences may influence the crops response to the treatment.

The decision pathways may be optimised across the farm to determine an ideal harvesting rotation. To summarise, higher yields are generally obtained by avoiding late ratooning and ensuring the crop is harvested at about 12 months of age. Crops that will be ploughed out may then be harvested in the last round thus minimising the amount of cane that must be ratooned late. To date little information has been collected on the time of planting, although McDonald and Lisson (2001) identified that crops planted early (May, June or July) are identifiably more productive than those planted later. It is possible to plan harvesting and planting operations to ensure crops are given an adequate amount of time (and solar radiation) to grow, whilst minimising the impact of late ratooning on cane yield. If growers or scientists wish to plan their harvesting operations over a number of years, then the network model presented here may be followed to evaluate harvesting options and the possible effect that timing has on yield for that block, or series of blocks. Researchers planning long term experiments should also consider the impact that harvest time may have on the results, and if necessary account for these differences with an appropriate experimental design.

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