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Incorporation of Within-Season Yield Growth into a Mathematical Programming Sugarcane Harvest Scheduling Model

Michael E. Salassi, Lonnie P. Champagne, and Benjamin L. Legendre

ABSTRACT

This study focuses on the development of a optimal harvest scheduling mathematical programming model which incorporates within-season changes in perennial crop yields. Daily crop yield prediction models are estimated econometrically for major commercially grown sugarcane cultivars. This information is incorporated into a farm-level harvest scheduling linear programming model. The harvest scheduling model solves for an optimal daily harvest schedule which maximizes whole farm net returns above harvesting costs. Model results are compared for a commercial sugarcane farm in Louisiana.

Key Words: *sugarcane, harvest scheduling, within-season yield growth.*

The sugarcane production sector in the United States is currently facing a significant challenge to its competitiveness. Passage of the Federal Agriculture Improvement and Reform Act of 1996 eliminated supply control measures for sugar as marketing allotments were suspended through the 2002 crop. As market prices for competing crops have declined since the passage of the new farm bill, sugar prices remained relatively stable into the 1999 crop year, resulting in significant increases in both sugarcane and sugarbeet acreage. Sugarcane acreage harvested for sugar increased from 829,500 acres in 1996 to a record 939,400 acres in 1999 (USDA, NASS, 1997 and 2000). The majority of this increase in sugarcane acreage occurred in Louisiana, where acreage harvested for sugar has increased by 100,000 acres since 1996. As the sugar industry in Florida approaches the limits of its productive capacity, sugarcane acreage in that state has increased moderately over the same period. Harvested acreage of sugarbeets in 1999 was estimated at a record 1.57 million acres, 200,000 acres more than in 1996.

Despite the continued recent expansion of sugarcane and sugarbeet acreage over the past several years, producer sugar prices had remained relatively stable as imports of sugar into the U.S. have decreased to support prices in the domestic market. U.S. sugar imports have declined from 2.77 million short tons, raw value, in 1996/97 to a projected 1.79 million short tons in 1999/00 (USDA, ERS, 2000). Under the GATT Agreement, however, the U.S. is required to import a minimum of 1.256 million shorts of tariff rate quota sugar annually. As a result, the reduction of sugar

The authors are associate professor and former research associate, Department of Agricultural Economics and Agribusiness, Louisiana State University Agricultural Center, and research leader, Sugarcane Research Unit, Agricultural Research Service, U. S. Department of Agriculture.

imports is no longer a viable policy tool to support domestic producer prices of sugar.

From January 1986 through September 1999, U.S. raw sugar prices remained above 20 cents per pound. With the initiation of harvest of the 1999 sugarcane and sugarbeet crops, projections of record domestic sugar production caused producer prices to decline drastically. By November 1999, raw sugar prices had dropped to 17.45 cents per pound (USDA, ERS, 2000). World sugar prices also dropped as foreign production also expanded. From 1994–1997, world raw sugar prices averaged over 12 cents per pound. By December 1999, world prices had dropped to 6 cents per pound. The NAFTA agreement established a declining tariff schedule for high-tier raw and refined sugar imported into the U.S. from Mexico (USDA, ERS, 1999). It has been estimated that a world price below 7.3 cents per pound in 1999 would introduce the probability of high-tier imports from Mexico. With declining high-tier tariff rates in following years, continued low world sugar prices increases the likelihood of Mexican imports. The possibility of increased Mexican imports, increased domestic sugarbeet production, and the inability to further reduce imports suggests that domestic raw sugar prices are likely to remain at below-average levels in the near term. In order to remain economically viable, sugarcane producers must be able to produce and harvest a sugarcane crop as efficiently and economically as possible.

Sugarcane is a member of the grass family and is chiefly valued for the juices extracted from its stems. Raw sugar is produced from these juices which is later refined into white sugar. Sugarcane is a perennial crop. One planting will generally allow for harvest over three to six years before replanting is necessary. As a sugarcane plant matures throughout the growing season, the amount of sucrose in the cane increases. Most of this sucrose production occurs when the plant is fully mature and begins to ripen (Alexander, 1973). Several studies have developed models to predict the sucrose level in sugarcane. Crane *et al.* (1982) developed a stubble replacement decision model for Florida sugarcane producers. They reported that sugar accumulation is a function of both sucrose accumulation and vegetative growth. The study suggested that the accumulation of sugar may be approximated as a quadratic function of time. Chang (1995), in research on Taiwanese sugarcane cultivars, suggested that individual cultivars have distinct sucrose maturation curves with different peak levels. This study concluded that the sugar content of a cultivar could be predicted as a function of time with reasonable accuracy and that the trend of sucrose accumulation within-season follows a second-order curve.

During the harvest season, older sugarcane (second stubble and older crops) is usually harvested first, followed by more recently planted crops, first stubble and then plantcane. Within this general order of crop harvest, producers attempt to estimate the sugar content of cane in the field in order to harvest fields at a point where the sugar content in the cane is at or near a maximum. Several methods have been developed for estimating sugar content in field cane. The core punch method uses a hand refractometer to estimate the Brix (percent soluble solids) of sugarcane, which is an indication of sucrose concentration. More sophisticated methods of sampling whole stalks are available, but require extensive equipment and labor (Barnes, 1974). If individual sugarcane cultivars have distinct sucrose maturation curves, which may vary up or down from year to year depending upon weather and other factors, then the sugar content of individual fields could be incorporated into a model which would determine an optimal order of harvest for all fields on a particular farm which would maximize total sugar produced (or total net returns received) on the farm.

Applications of crop harvest scheduling models, using some type of operations research procedure, are most common in the timber industry. Most of these applications involve the use of linear programming or simulation models. Recent studies have investigated the use of Monte-Carlo integer programming (Nelson, *et al.,* and Daust and Nelson), bayesian concepts (Van Deusen), and tabu search procedures (Brumelle, *et al.*). Several studies have developed crop growth models to predict the harvest date of agricultural crops (Lass, *et al.*, Malezieux, and Wolf). However, most of these studies use optimal harvest decision rules based upon agronomic characteristics of the crop rather than economic principles.

Several studies have addressed various aspects of sugarcane productivity and harvest operations. Millhollon and Legendre studied the use of glyphosate, an artificial crop ripener used in sugarcane production, on sugarcane yield. Glyphosate (trade name POLADO®) is labeled for use only on ratoon or stubble sugarcane crops in Louisiana, Florida and Texas. Their study indicated that annual glyphosate ripener treatments on sugarcane will usually increase mean annual sugar yield, but the magnitude of the increase depended on cultivar tolerance to the treatments. Two studies have evaluated the economics of sugarcane stubble crop replacement in Florida (Crane, *et al.*) and Louisiana (Salassi and Milligan). These studies evaluated the optimal crop cycle length by comparing annualized future net returns from replanting to estimated returns from extending the current crop cycle for another year. Semenzato developed a simulation algorithm for scheduling sugarcane harvest operations at the individual farm level to minimize the lapse of time between the end of burning and processing. The model calculated the maximum size of a field which could be harvested and have all of its cane processed within 15 days. This study focused on farm size and equipment availability in order to efficiently use limited resources in a timely manner. A recent study in Australia did determine optimal sugarcane harvest schedules which maximized net returns using mathematical programming procedures (Higgins, *et al.*, and Muchow, *et al.*). However, the modeling framework in this study encompassed many farms within a production region over a multiyear harvest period. Furthermore, the smallest unit of time within the harvest scheduling model was one month.

The purpose of this article is to present a methodology for the incorporation of within-season sucrose accumulation in sugarcane into an optimal single-season, daily harvest scheduling model at the individual farm level. The objective of the general modeling procedure is to capture the dynamic effect of sucrose accumulation during the growing season and to use this information, within a mathematical program modeling framework, in determining when specific sugarcane fields should be harvested in order to maximize total farm net returns. Data for this analysis will be obtained from Agricultural Research Service, USDA experimental research tests conducted in Louisiana over several years. Sucrose levels were estimated econometrically as a function of time for major cultivars currently produced commercially in the state. These data are then incorporated into a mathematical programming model which determines an optimal harvest schedule that maximizes whole farm net returns for a given farm situation.

Sugar Prediction Models

The amount of raw sugar in a field of sugarcane is a function of several variables. Two important measures of sugarcane yield include tons of sugarcane and pounds of raw sugar produced per acre. The relationship between sugar per acre and factors which influence it can be stated simply as follows:

$$(1) \quad S_A = TRS \times TONS = TRS \times POP \times STWT$$

where S_A is total pounds of raw sugar per acre, TRS is theoretical recoverable sugar in pounds of sugar per ton of cane, TONS is the tons of sugarcane produced per acre, POP is the per-acre population of sugarcane stalks in the field, and STWT is the stalk weight. Although the population of sugarcane stalks within a field can be assumed to be constant throughout the harvest season, the same assumption cannot be made for the other factors in the relationship. Theoretical recoverable sugar and stalk weight both increase as the harvest season progresses. In order to incorporate this yield increase within a whole-farm mathematical programming harvest scheduling model, estimates must be obtained for the predicted levels of each of these factors for each variety of sugarcane produced on the farm for each day of the harvest season.

Sucrose maturity data developed at the ARS, USDA Sugar Cane Research Unit in Houma, Louisiana, were used in the analysis. Stalk weight and sugar content of the commercial sugarcane cultivars grown in Louisiana were sampled at intervals during the harvest season from 1981 to 1996. The data included measurements of theoretical recoverable sugar, sugar per stalk and stalk weight by julian date for 3 to 16 years, depending upon variety. Harvest season for sugarcane in Louisiana historically typically runs from the first of October through the end of December. Observations for each commercial cultivar ranged from julian date 255 to 346 or approximately the middle of September through the middle of December. The age of the crop (plantcane or stubble) was also included. *Plantcane* refers to a sugarcane crop planted last year which will be harvested for the first time this year. The second harvested crop of that field the following year is referred to as *first stubble,* and the following crop is referred to as *second stubble.*

Models were estimated for stalk weight and sugar per stalk in order to predict the amount of sugarcane and raw sugar in the field for each day of the harvest season. Previous research suggest that a quadratic model can be used to model sugar accumulation. Graphical analysis of both stalk weight as well as sugar-per-stalk data suggested that these variables could be estimated using a semi-log functional form. Econometric models of stalk weight and sugar per stalk were estimated for each cultivar as follows:

$$(2)\qquad STWT_{ct} = \beta_0 + \beta_1 LNJD + \beta_2 CROP + \sum_{i=81}^{95} \beta_i YEAR_i + \epsilon$$

$$(3)\qquad SPS_{ct} = \alpha_0 + \alpha_1 LNJD + \alpha_2 CROP + \sum_{i=81}^{95} \alpha_i YEAR_i + \epsilon$$

where $STWT_{ct}$ represents stalk weight in pounds per stalk of cultivar *c* on day *t,* SPS_{ct} represents sugar per stalk in pounds of cultivar *c* on day *t,* LNJD is the natural log of julian date, CROP is an indicator variable representing crop age as either plantcane or stubble crop, and $YEAR_i$ represents indicator variables for different years. These annual indicator variables were included to capture the relationship that sugarcane cultivars have distinct sugar accumulation curves which shift vertically from year to year depending upon weather and other factors. The base year in this estimation was 1996 and the indicator variables serve the purpose of adjusting the sugar accumulation curve to factors in a given year. All models were estimated using SAS (SAS Institute, version 6.12). The estimates of stalk weight and sugar per stalk were combined with stalk populations to estimate sugar cane and sugar yield for each field.

Estimated models of stalk weight and sugar per stalk for each sugarcane cultivar are shown in Tables 1 and 2. Julian date (LNJD) and crop age (CROP) were found to be highly significant in the stalk weight prediction models (Table 1). Positive signs on the julian date variable indicate that stalk weight increases throughout the harvest season. The signs on the significant crop age variables were negative, as expected, indicating that stalk weight tends to be greater for plantcane crops than for older stubble crops. Coefficients of determination for specific variety models ranged from 0.36 to 0.81. In several of the estimated equations indicator variables for years were significant which implies that the stalk weight growth curves vary from year to year depending upon weather and other factors. Similar results were found for the sugar-per-stalk prediction models (Table 2). Julian date was highly significant with positive coefficients indicating sugar accumulation increases during the harvest season and crop age was found to be significant in six of the ten equations estimated. The sign on the estimated coefficient for crop age was negative in each of the six equations in which it was significant. Coefficients of determination were high in the sugar-per-stalk models ranging from 0.78 to 0.90. Durbin-Watson tests for autocorrelation either failed to reject the hypothesis of no autocorrelation or were inconclusive. The White test for heteroscedasticity (White) failed to reject the hypothesis of homoscedasticity for each cultivar tested.

Farm Level Production Estimates

The estimated-stalk-weight and sugar-per-stalk models can be used to predict the sugar yield on a given farm in a specific year. Prediction of stalk weight and sugar per stalk per day across a given harvest season may require an adjustment of the predicted values for the crop's stalk weight and sugar content in the current year. Stalk weight and sugar content can be obtained from samples taken in the field. A sample data set was developed from information collected from a commercial sugarcane farm in Louisiana for the 1996 harvest season. Characteristics of the farm are presented in Table 3. Stalk number estimates were collected on September 18–19 and October 2, 1996 from each of the fields on the farm. The number of samples taken per field depended upon the size of the field, but a target of one count was taken for every one and half acres. In a randomly selected area of the field, a 25-foot distance was measured between the middle of two rows. The number of millable stalks within that distance was then counted and converted to an estimate of stalk population number per acre and field. Sample stalk counts for each field were then averaged to estimate a mean stalk population per field. Ten-stalk samples were cut from randomly selected locations in each field on October 7 and 9, 1996. Each stalk sample was weighed and milled to obtain a juice sample for analysis. The average stalk weight and estimated theoretical recoverable sugar from the juice analysis were combined with field information to develop stalk-weight and sugar-per-stalk measurements by field.

Prediction models of stalk weight and sugar per stalk were then adjusted to the 1996 crop year. The adjustments were calculated by subtracting the predicted value of stalk weight and sugar per stalk, $STWT_{Predicted}$ and $SPS_{Predicted}$, on the day of sampling from the actual field measurements, $STWT_{Actual}$ and SPS_{Actual} as shown in equations 4 and 5. This adjustment was incorporated into each model as a parallel shift in the intercept.

$$(4)\quad \beta_0' = \beta_0 + (STWT_{Actual} - STWT_{Predicted})$$

$$(5)\quad \alpha_0' = \alpha_0 + (SPS_{Actual} - SPS_{Predicted})$$

Stalk weight and sugar per stalk were then estimated for each day of the harvest season using the estimated prediction models with adjusted intercepts.

Estimates of tons of sugarcane per acre and pounds of raw sugar per acre were calculated by multiplying stalk weight and sugar per stalk by stalk population as follows:

$$(6)\quad CANE_{ft} = POP_f \times STWT_{ct}/2000$$

$$(7)\quad SUGAR_{ft} = POP_f \times SPS_{ct}$$

where $CANE_{ft}$ is the estimated tons of sugarcane per acre in field f on julian date t, POP_f is the estimated stalk population per acre in field f, $STWT_{ct}$ is the estimated stalk weight in pounds for cultivar c on julian date t, $SUGAR_{ft}$ is the estimated pounds of raw sugar per acre in field f on julian date t, and SPS_{ct} is the estimated sugar per stalk in pounds for cultivar c on julian date t. Since POP_f, $STWT_{ct}$ and SPS_{ct} are predicted values with associated variances, direct multiplication would cause the estimated variances of predicted cane and sugar yields to be very large, making the prediction intervals considerably wider (Griffths *et al.* 1993). As a result, the relationships in equations 6 and 7 were converted to log form for calculation. Estimated yields per field were then adjusted for field conditions (recovery and trash) and difference between theoretical recoverable sugar and commercial recoverable sugar (equations 8 and 9).

$$(8)\quad ADJCANE_{ft} = CANE_{ft} \times (1 + TRASH_f) \times FIELDRECOVERY_f$$

$$(9)\quad ADJSUGAR_{ft} = SUGAR_{ft} \times 0.8345 \times SCALEFACTOR$$

$ADJCANE_{ft}$ represents the tons of sugarcane actually harvested from the field and delivered

Table 1. Parameter Estimates for Stalk Weight Prediction Models

	Sugarcane Varieties									
VAR	LCP 82-89	LHo 83-153	CP 78-318	CP 70-321	CP 65-357	CP 72-370	CP 74-383	LCP 85-384	LCP 85-454	HoCP 85-845
INT	−7.717**	−6.747**	−8.868**	−6.672**	−6.884**	−5.550**	−6.718**	−9.192**	−13.976**	−9.419**
	(1.513)	(1.442)	(1.361)	(0.964)	(0.994)	(0.876)	(1.460)	(2.601)	(2.759)	(2.445)
LNJD	1.805**	1.621**	2.040**	1.652**	1.718**	1.441**	1.608**	1.988**	2.985**	2.075**
	(0.265)	(0.253)	(0.237)	(0.168)	(0.173)	(0.153)	(0.254)	(0.456)	(0.484)	(0.429)
CROP	−0.373**	−0.312**	−0.295**	−0.330**	−0.352**	−0.389**	−0.192**	−0.158*	−0.296**	−0.202**
	(0.050)	(0.047)	(0.045)	(0.032)	(0.033)	(0.028)	(0.047)	(0.083)	(0.089)	(0.078)
1981	—	—	—	0.190**	0.097	0.107	—	—	—	—
				(0.074)	(0.073)	(0.072)				
1982	—	—	—	0.091	−0.294**	0.013	—	—	—	—
				(0.076)	(0.076)	(0.074)				
1983	—	—	—	−0.154**	−0.372**	−0.109	−0.052	—	—	—
				(0.076)	(0.076)	(0.074)	(0.093)			
1984	—	—	—	−0.233**	−0.474**	−0.090	0.020	—	—	—
				(0.074)	(0.074)	(0.073)	(0.090)			
1985	—	—	—	−0.215**	−0.610**	−0.152**	−0.108	—	—	—
				(0.074)	(0.073)	(0.072)	(0.089)			
1986	—	—	—	−0.227**	−0.397**	−0.144*	−0.081	—	—	—
				(0.074)	(0.073)	(0.072)	(0.089)			
1987	—	—	−0.347**	−0.483**	−0.509**	−0.392**	−0.278**	—	—	—
			(0.098)	(0.083)	(0.083)	(0.080)	(0.103)			
1988	—	—	−0.055	0.001	−0.181**	−0.138*	0.088	—	—	—
			(0.087)	(0.074)	(0.073)	(0.072)	(0.090)			
1989	—	—	−0.101	0.092	−0.037	0.016	0.181*	—	—	—
			(0.089)	(0.076)	(0.076)	(0.074)	(0.093)			
1990	0.214**	—	0.187**	0.259**	0.034	0.212**	—	—	—	—
	(0.083)		(0.086)	(0.074)	(0.084)	(0.072)				
1991	−0.862**	−0.813**	−0.637**	−0.981**	−0.985**	−0.805**	—	—	—	—
	(0.086)	(0.076)	(0.089)	(0.076)	(0.076)	(0.074)				
1992	−0.459**	−0.372**	−0.317**	−0.483**	−0.572**	−0.364**	−0.329**	—	—	—
	(0.083)	(0.074)	(0.086)	(0.074)	(0.073)	(0.072)	(0.090)			

Table 1. (Continued)

1993	−0.374**	−0.400**	−0.375**	−0.280**	−0.359**	−0.293**	−0.312**	—	—	—
	(0.083)	(0.074)	(0.086)	(0.074)	(0.073)	(0.072)	(0.090)			
1994	−0.009	−0.160**	−0.025	−0.098	−0.287**	−0.109	−0.146	−0.061	−0.027	−0.090
	(0.083)	(0.074)	(0.086)	(0.074)	(0.073)	(0.072)	(0.089)	(0.099)	(0.104)	(0.093)
1995	−0.161*	−0.130*	−0.081	−0.000	−0.222**	−0.116	—	0.061	−0.093	−0.033
	(0.083)	(0.074)	(0.086)	(0.074)	(0.073)	(0.072)		(0.099)	(0.104)	(0.093)
Adj. R^2	0.81	0.79	0.73	0.80	0.78	0.80	0.49	0.36	0.59	0.44
n	72	62	98	158	158	153	118	36	33	36
DW	1.77	2.03	1.89	1.94	2.25	1.84	1.55	2.42	1.87	2.18
White prob.	0.34	0.89	0.74	0.41	0.34	0.87	0.87	0.36	0.93	0.75

Notes: Number in parenthesis are standard errors. Single and double asterisks (*) denote statistical significance at the 10% and 5% level, respectively, *n* is the sample size, *DW* is the Durbin-Watson statistic, and *White prob.* is the probability level of the White test for heteroscedasticity. INT is the intercept, LNJD is the natural log of julian date, CROP is a indicator variable for crop age (plantcane vs. stubble), and 1981–1995 are indicator variables for individual years.

to the mill for processing. $TRASH_f$ is a percentage estimate of leaf matter and other trash in the harvested cane, and $FIELDRECOVERY_f$ is a percentage estimate the amount of sugarcane in the field actually recovered by harvest operations. Expected levels of trash and field recovery were determined on an individual field basis. $ADJSUGAR_{ft}$ represents the actual pounds of raw sugar recovered from the processed cane. The estimated sugar yield is multiplied by a standard factor (0.8345) to convert theoretical recoverable sugar into commercially recoverable sugar. This standard is used by sugar mills to estimate recovery since the actual liquidation factor will not be known until the end of season. Accounting for differences from the laboratory analysis to the fields, the estimated sugar per field is reduced by a scale factor. The assumed scale factor is 92 percent.

Mathematical Programming Formulation

The determination of a harvest schedule was formulated as a linear mathematical programming model which maximized producer net returns above harvest costs over total farm acreage. Farm returns were derived from the sale of sugar and molasses less a percentage of the total production as a "payment-in-kind" to the factory for processing and a percentage of producer's share paid to the land owner as rent. Since preharvest production costs were assumed to be independent of harvest operations, only harvest costs are included in the model. Harvest costs are assumed to be a function to the total tonnage of sugarcane harvested. The objective function for the model was defined as follows:

$$(10) \quad Z = (P_s \times S_p) + (P_m \times M_p) - (C_h \times T_t)$$

where Z represents total farm level producer net from sugar and molasses production above harvesting costs, P_s represents the price received per pound of sugar (cents per pound), S_p is the producer's share of sugar produced (pounds), P_m is the price of molasses (dollars per gallon), M_p is the producer's share of molasses (gallons), C_h is the cost of harvesting

Table 2. Parameter Estimates for Sugar-per-Stalk Prediction Models

VAR	LCP 82-89	LHo 83-153	CP 79-318	CP 70-321	CP 65-357	CP 72-370	CP 74-383	LCP 85-384	LCP 85-454	HoCP 85-845
	Sugarcane Varieties									
INT	−3.511**	−3.296**	−4.064**	−3.470**	−3.932**	−2.442**	−3.05**	−4.081**	−4.50**	−3.273**
	(0.188)	(0.228)	(0.167)	(0.133)	(0.131)	(0.122)	(0.180)	(0.259)	(0.328)	(0.266)
LNJD	0.664**	0.626**	0.764**	0.663**	0.741**	0.486**	0.576**	0.757**	0.849**	0.623**
	(0.033)	(0.040)	(0.029)	(0.023)	(0.023)	(0.021)	(0.031)	(0.045)	(0.057)	(0.046)
CROP	−0.024**	−0.014*	−0.017**	−0.029**	−0.027**	−0.041**	−0.005	0.004	0.006	−0.006
	(0.006)	(0.007)	(0.005)	(0.004)	(0.004)	(0.004)	(0.005)	(0.008)	(0.010)	(0.008)
1981	—	—	—	0.018*	0.027**	0.010	—	—	—	—
				(0.010)	(0.009)	(0.010)				
1982	—	—	—	−0.011	−0.037**	−0.009	—	—	—	—
				(0.010)	(0.010)	(0.010)				
1983	—	—	—	−0.028**	−0.022**	−0.035**	−0.05	—	—	—
				(0.010)	(0.010)	(0.010)	(0.011)			
1984	—	—	—	−0.041**	−0.042**	−0.021**	0.012	—	—	—
				(0.010)	(0.009)	(0.010)	(0.011)			
1985	—	—	—	−0.037**	−0.052**	−0.034**	−0.012	—	—	—
				(0.010)	(0.009)	(0.010)	(0.011)			
1986	—	—	—	−0.032**	−0.003	−0.022**	0.006	—	—	—
				(0.010)	(0.009)	(0.010)	(0.011)			
1987	—	—	−0.005	−0.033**	−0.008	−0.038**	0.011	—	—	—
			(0.012)	(0.011)	(0.011)	(0.011)	(0.012)			
1988	—	—	−0.004	−0.006	−0.004	−0.022**	0.032**	—	—	—
			(0.010)	(0.010)	(0.009)	(0.010)	(0.011)			
1989	—	—	0.001	0.003	0.028**	−0.014	0.035**	—	—	—
			(0.011)	(0.010)	(0.010)	(0.010)	(0.011)			
1990	0.011	—	0.005	0.006	0.009	0.003	—	—	—	—
	(0.010)		(0.010)	(0.010)	(0.011)	(0.010)				
1991	−0.097**	−0.113**	−0.070**	−0.147**	−0.079**	−0.108**	—	—	—	—
	(0.010)	(0.012)	(0.011)	(0.010)	(0.010)	(0.010)				
1992	−0.034**	−0.044**	−0.017	−0.047**	−0.014	−0.047**	−0.013	—	—	—
	(0.010)	(0.011)	(0.010)	(0.010)	(0.009)	(0.010)	(0.011)			

Table 2. (Continued)

1993	−0.047**	−0.064**	−0.039**	−0.049**	−0.012	−0.033**	−0.033**	—	—	—
	(0.010)	(0.011)	(0.010)	(0.010)	(0.009)	(0.010)	(0.011)			
1994	0.004	−0.020	0.012	−0.021**	−0.008	−0.011	−0.006	−0.008	−0.001	−0.019*
	(0.010)	(0.011)	(0.010)	(0.010)	(0.009)	(0.010)	(0.011)	(0.009)	(0.012)	(0.010)
1995	−0.019*	−0.017	−0.008	0.005	−0.015	−0.014	—	−0.005	−0.007	−0.017
	(0.010)	(0.011)	(0.010)	(0.010)	(0.009)	(0.010)		(0.009)	(0.012)	(0.010)
Adj. R^2	0.89	0.86	0.90	0.89	0.89	0.86	0.78	0.89	0.87	0.83
n	72	62	98	158	158	153	118	36	33	36
DW	2.01	2.44	2.13	1.99	2.23	1.88	1.76	2.74	1.49	2.31
White prob.	0.37	0.39	0.86	0.20	0.82	0.74	0.88	0.14	0.56	0.39

Notes: Number in parenthesis are standard errors. Single and double asterisks (*) denote statistical significance at the 10% and 5% level, respectively, *n* is the sample size, *DW* is the Durbin-Watson statistic, and *White prob.* is the probability level of the White test for heteroscedasticity. INT is the intercept, LNJD is the natural log of julian date, CROP is a indicator variable for crop (plantcane vs. stubble), and 1981–1995 are indicator variables for individual years.

sugarcane (dollars per ton), and T_t is the total tons of sugarcane harvested.

The model consists of two sets of resource limiting constraints and several transfer rows. The functional constraints of the model were defined as follows:

$$(11) \quad \sum_{d=1}^{n}\sum_{f=1}^{m}(X_{df}\cdot S_{df}) - S_t = 0$$

$$(12) \quad \sum_{d=1}^{n}\sum_{f=1}^{m}(X_{df}\cdot T_{df}) - T_t = 0$$

$$(13) \quad 0.029\cdot S_t - M_t = 0$$

$$(14) \quad a\cdot S_t - S_p = 0$$

$$(15) \quad b\cdot M_t - M_p = 0$$

$$(16) \quad \sum_{d=1}^{n} X_{df(1)} = 1$$

$$\vdots \qquad \vdots$$

$$\sum_{d=1}^{n} X_{df(m)} = 1$$

$$(17) \quad \sum_{f=1}^{m}(X_{d(1)f}\cdot T_{d(1)f}) = Q_1$$

$$\vdots \qquad \vdots$$

$$\sum_{f=1}^{m}(X_{d(n)f}\cdot T_{d(n)f}) = Q_n$$

All of the equations follow a similar format with the subscripts f and d identifying the field and date of harvest, respectively. The model has m fields and n days. X_{df} is the percent of field f harvested on day d. The predicted yield of sugar (pounds) and sugarcane (tons) for field f on day d is S_{df} and T_{df}, respectively. S_t, T_t and M_t are the total pounds of sugar, tons of sugarcane and gallons of molasses produced on the farm. The producer's shares of sugar, S_p, and molasses, M_p, are calculated by taking the producer's share of sugar, a, and molasses, b, from the totals. The daily quota, Q_d, is the maximum tons of sugarcane that can be harvested and delivered to the mill each day. All dates are recorded using julian date.

The first two functional constraints are transfer rows that accumulate the total pounds of sugar produced (equation 11) and tons of sugarcane harvested (equation 12), respective-

Table 3. Sample Farm Acreage and Production Characteristics

Farm data:			
Farm size (harvestable acreage)		556.9	
Number of fields		112	
Smallest field (acres)		0.3	
Largest field (acres)		19.6	
Variety data:			
LCP82-89	plantcane	1 field	1.3 acres
LCP82-89	stubble crop	13 fields	44.0 acres
LHo83-153	plantcane	2 fields	6.7 acres
LHo83-153	stubble crop	6 fields	31.8 acres
CP79-318	stubble crop	4 fields	14.2 acres
CP70-321	plantcane	12 fields	74.2 acres
CP70-321	stubble crop	43 fields	228.9 acres
CP65-357	stubble crop	7 fields	38.0 acres
CP72-370	plantcane	3 fields	13.6 acres
CP72-370	stubble crop	14 fields	61.7 acres
LCP85-384	plantcane	5 fields	37.3 acres
LCP85-384	stubble crop	2 fields	5.2 acres

ly. Equation 13 calculates the gallons of molasses recovered by multiplying the pounds of sugar produced by a conversion factor of 0.029. Equations 14 and 15 calculate the producer's share of sugar and molasses, respectively. Equation sets 16 and 17 each represent a system of binding constraints. Equation 16 forces the model to choose each field exactly once during the harvest season, although the harvest of a specific field may be over consecutive days. Decision variables in equation 16 were continuous and represented the percentage of a field harvested on any available day. Since most of the 112 fields included in the analysis were relatively small in acreage relative to the daily harvest quota in tons of sugarcane, the linear programming solution to the problem resulted in most fields being harvested on a single day. Harvest of some fields was split over more than one day. Since the yield curves were concave in the days of the harvest season, harvest of fields not entirely completed in one day were harvested on consecutive days. This result is realistic in that a producer may begin harvest of a field on one day and complete it the next. Given the dimensions of the problem analyzed here, the LP relaxation solution was solved, rather than defining the decisions variables as binary integers. Equation 17 creates a daily limit on the tons of sugarcane that may be harvested in one day. Each day has a constraint row that limits the tons of cane harvested to less than a specified daily quota amount.

Results

Three harvest scenarios were solved by the harvest scheduling model. The solution results for each of these scenarios are shown in Table 4. The first solution represents results from simulating the producer's actual harvest schedule. After the 1996 harvest season ended, the producer provided information on the specific day each field was harvested as well as actual sugar yields obtained. The actual harvest schedule solution in Table 4 is based on the date of actual harvest by field and the predicted sugarcane and sugar yields from the estimated prediction models. Sugarcane (tons) and sugar (pounds) yields per acre achieved by the producer closely matched predicted yields from the estimated models. Predicted total sugarcane production was 16,964 tons of sugarcane compared to the actual production of 16,639 tons reported by the producer. Estimated producer returns above harvest costs for the actual harvest schedule were $326,771. Average sugarcane yield over the whole farm was 30.5 tons per acre, resulting in an average sugar yield of 5,573 pounds per acre.

A second harvest scheduling model was solved for a solution in which harvest dates for individual fields were constrained to specified intervals. In Louisiana, sugarcane harvest begins with fields which contain the oldest stubble crops (second stubble and older), then proceeds to younger, first stubble crops. All stubble crop fields are usually harvested first. Within each stubble group, varieties are usually are in order of maturity class: very early, early, and mid-season (Faw). Finally, fields which are being harvested for the first time, containing plantcane, are harvested at the end of the harvest season in order to avoid damage to future stubble crops from early harvest. Plantcane fields are usually harvested beginning with varieties that deteriorate rapidly after a freeze and ending with harvest of varieties that deteriorate more slowly after a freeze. In the constrained harvest model, possible harvest dates were specified for each field in the sample data set which conformed to traditional harvesting practices. Generally stated, these harvest date ranges began with second stubble harvest beginning on October 1st and continuing into November. First stubble harvest began in late October and continued through November. Plantcane harvest began in late November and continued through the end of December. Solution results from this model indicated that sugar production and net returns could be increased with relatively minor adjustments to the actual harvest schedule. Optimal adjustment of harvest of individual fields resulted in a projected increase in net returns by $17,360, or approximately $31 per harvested acre. Average harvested yield of sugarcane increased by 0.7 tons per acre resulting in an increase in average sugar yield per acre of 263 pounds. Analysis of individual field results indicated that the optimal harvest date changed an average of 13 days from the actual harvest date with some fields being harvested earlier and other fields harvested later in the season.

An unconstrained harvest scheduling model was also solved for comparison purposes. In this model no constraints were placed on days in which fields could be harvested. Any field on the farm was allowed to be harvested on any day within the harvest season. Estimated net returns were $378,147, or $51,376 higher than the actual harvest schedule and $34,016 higher than the constrained optimal solution schedule. This unconstrained solution is not realistic in the sense that plantcane would generally not be harvested before stubble crops. Early harvest of plantcane may increase sugar production in the current year, but it would have a significant adverse effect on sugar yields of future stubble crops. However, it does give some indication of the current returns forgone in order to maximize future returns.

Conclusions

Elimination of sugar marketing allotments and the resulting impacts of trade agreements on U.S. raw sugar import levels has limited the ability of the U.S. to support domestic raw sugar prices in the presence of large domestic stocks. The long-run viability of the sugar industry will depend upon finding ways to produce sugar more economically through reduction of production costs and the efficient management of resources available. Maximizing net returns for a whole farm rather than trying to produce the maximum amount of sugar per field should be a primary goal of producers. The purpose of this study was to develop a methodology to assist scheduling the sequence in which sugarcane fields are harvested to maximize producers' economic returns. The specific objectives of this study were to develop models which would estimate the increase in stalk weight and accumulation of sugar per stalk within the harvest season and to develop a mathematical programming algorithm that selects a harvesting schedule which maximizes net returns from sugar production above harvest cost.

Estimating the effect of time on the vegetative growth and sucrose accumulation in sugar cane was accomplished with least squares regression. Models which predicted stalk weight and sugar per stalk by cultivar were estimated as a function of julian date and crop age as well as indicator variables repre-

Table 4. Comparison of Actual Harvest Schedule with Optimal Harvest Schedules

Solution Summary	Actual Harvest Schedule[1]	Constrained Optimal Harvest Schedule	Unconstrained Optimal Harvest Schedule
Returns above harvest cost	$326,771	$344,131	$378,147
Total sugar (pounds)	3,103,709	3,250,056	3,527,466
Total cane (tons)	16,964	17,373	17,927
Total molasses (gallons)	90,008	94,252	102,297
Acres	556.9	556.9	556.9
Average CRS (pounds sugar/ton)	183.0	187.1	196.8
Sugar per acre (pounds)	5,573	5,836	6,334
Cane per acre (tons)	30.5	31.2	32.2

[1] This schedule includes the producer's actual harvest schedule with total sugar and cane production estimated from prediction models. Producer records report actual production of 16,639 tons of sugarcane and 2,961,500 pounds of sugar.

senting years of production with different growing conditions. These models were then used to predict sugar yields by cultivar and field for a sample farm. The optimization linear programming model used the estimated accumulation of stalk weight and sugar per stalk with field information to generate yield predictions. The predicted yields were used to select a harvest schedule subject to constraints that maximized producer net returns above harvest cost. The optimization model predicted reasonable estimates of production on a commercial sugarcane farm in Louisiana.

The ability to predict sugarcane tonnage and raw sugar yields allows producers and mill personnel to more effectively plan the harvest season based on the current status of the crop. A producer could potentially analyze the yield of each cultivar of sugarcane in the farm's crop mix and make decisions concerning future plantings. Optimizing harvest schedules will potentially recover more sugar from the fields, which directly increases the sugar recovered by the mills. Knowledge of the size and maturity stage of the crop will allow mills to more effectively assign delivery quotas among producers and plan the harvest season to maximize sugar production. Interest in site-specific farming using global positioning satellites (GPS) and global information system (GIS) is growing among sugarcane producers, but the limiting factor is the ability to attribute yield to location. The model developed in this study allows for the possibility of predicting sugar yield for individual fields. This information can be useful in designing fertility programs, weed control programs and in making crop replacement decisions on an individual field basis.

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