Causal Factors of Daily Variation in Commercial Cane Sugar Value of Processed Sugarcane Throughout the Milling Season in Northeast Thailand

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ABSTRACT

Large daily variation in the commercial cane sugar (CCS) value of sugarcane processed by sugar mills throughout the milling season is a major problem of the sugar industry in Thailand and other Asian countries. To alleviate this problem, knowledge on their causal factors is needed. This study was conducted to investigate the main causal factors for this daily CCS variation. The Mitr Phu Wiang Sugar Mill in Northeast Thailand was chosen as a case example. The objective was to identify the main causal factors for the daily variation in the CCS value of sugarcane processed by the mill during the 2014/2015 milling season. A village in the service area of the mill was selected as the site for data collection. A survey based on a questionnaire was used to collect data on field characteristics and crop management practices of all 123 sugarcane fields in the village in the 2014/2015 cropping season. Samples of sugarcane were collected from individual fields at harvest for CCS determination. Data on CCS values of all sugarcane processed by the mill were also obtained from the mill. A multiple regression analysis was used in determining the significant causal factors for the daily CCS variation. The results revealed that plant age-at-harvest and crop class were the two main causal factors accounting for 68% of the variation. The variation can potentially be substantially reduced by changing the harvest time of fields harvested either too early or too late. This, however, would involve a redesign of the entire supply chain management system and a lot of operational changes would also be needed for its implementation. These changes are also necessary for the use of combine harvesters which will be unavoidable in the future due to scarcity of labor for manual harvesting. The approach proposed based on the results of this study could potentially be used for other mills in Thailand and in other countries with similar conditions.

Keywords: CCS, CCS variation, sugarcane production, sugarcane quality, supply chain management

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INTRODUCTION

Sugarcane *(Saccharum officinarum*) is one of the most valuable agricultural commodities in the world, as the crop is a major source of raw material for sugar and ethanol production. Asia is the major production area of the crop, with Thailand being ranked fourth in the world for sugarcane production (FAO, 2016). Thailand is also one of the world's leading sugar-exporting countries, each year exporting more than 7.25 million tons, earning about 5 billion US $ in foreign exchange. The major growing area of the crop is in the Northeast region, which, in 2015, accounted for 52.5% of the cultivated area and 52.1% of the sugarcane production of the country (OAE, 2016). A major problem of the sugar industry in Thailand is the variation in the sweetness of sugarcane, as measured by the commercial cane sugar (CCS) value, that enters the sugarcane processing mills during the milling season (Piewthongngam *et al.,* 2009). Records at the Mitr Phu Wiang Sugar Mill in Khon Kaen province, a mill owned by the large sugar company Mitr Phol Group, show that the CCS values of sugarcane delivered to the mill for processing each day during the 2010/2011 milling season differed substantially, with the range of the differences being about 6 units throughout the milling season (unpublished data). Large daily CCS variation has also been observed in other mills in Thailand (unpublished data), and is presumably a problem in other countries, particularly in Asia. Reducing this variation by raising the CCS values in low-CCS fields would increase the seasonal CCS value of the mills, enabling them to produce more sugar from the same amount of sugarcane. In the 2010/2011 milling season, the Mitr Phu Wiang Sugar Mill processed 4.42 million tons of sugarcane which produced about 0.50 million tons of sugar. It was estimated that, for this mill alone, an increase in CCS for one unit would increase the value of the amount of sugar produced to more than 20 million US $ per year. There is a clear potential financial benefit from this if it could be achieved for all the mills in the country. The same potential benefit could be anticipated for sugarcane processing in other countries.

The CCS value provides an estimate of the percentage of recoverable sugar (sucrose) from cane. It is calculated from a function of Brix and Pol in juice and cane fiber content, and is used as a criterion to determine the sweetness quality of sugarcane (Engelke, 2002; Albertson and Grof, 2004). Several factors had been shown to affect the CCS value of sugarcane, including varieties, crop classes, planting season, nutrient and water management, diseases and insect pests, lodging, time of harvesting, crop age-at-harvest (crop duration), transportation, and duration of post-harvest handling (Kingston and Hyde, 1995; Mitr Phol R&D Co., 2007). These causal factors affect CCS differently, but are somewhat related to each other, and are location specific. Intra-field variation of CCS has also been observed. Gravel in the soil, high leaf nitrogen, calcium to magnesium ratio in the leaf and depth of the root zone were identified as the causal factors (Kingston and Hyde, 1995). Year and month of harvest were also found to influence the CCS value in an area in Australia (Lawes *et al.*, 2002). In Thailand, the duration of cutting-to-crushing and crop age-at-harvest have been shown to account for 71.8% of the variation in the CCS of sugarcane grown under contract farming conditions in three provinces in the Central region (Tukaew et al., 2016). As the causal factors for CCS variation differed in different contexts, to reduce the CCS variation in a given area, the causal factors specific to the area need to be identified. This study took the Mitr Phu Wiang Sugar Mill in Northeast Thailand as a case example. The objective was to identify the causal factors for daily variation in CCS at this mill, to allow the mill to formulate appropriate measures for reducing the variation. The approach could potentially be used for other mills with a similar problem, both in Thailand and in other countries.

MATERIALS AND METHODS

The Study Site

A village in the service area of the Mitr Phu Wiang Sugar Mill, Hin Kong village in Ban Fang district of Khon Kaen province, was selected for this study. This village is under the sugarcane improvement program of the mill. It is located about 45 km southwest of Khon Kaen city and about 20 km from the mill (16° 27′ 12″ N, 102° 38′ 18″ E). Its area is characterized by undulating terrains with sandy soils, and is representative of the major land and soil types used for sugarcane cultivation in Northeast Thailand. The village normally supplies sugarcane to the Mitr Phu Wiang Sugar Mill at different times throughout the milling season.

Data Collection

Data collection was done during the 2014/2015 milling season, from November 2014 to the end of April 2015. A total survey approach was used in which data were collected on field characteristics, crop management and CCS for all sugarcane fields in the village. Data were collected in three periods (i.e., before harvesting, at harvesting, and after harvesting) for each field.

Data collected before harvesting included land type (upland or lowland), soil type, crop cultivar, crop class (planted crop or ratoon crop number), planting season (for planted crop), land preparation (for planted crop) or field management after crop cutting (for ratoon crop), crop starting date (planting date for planted crop or date of cutting the previous crop for ratoon crop), kind and amount of chemical fertilizers and/or manure applied and number of applications, number of irrigations applied, number and method of weeding, and incidences of insects and diseases. Data collected for the same fields after harvesting included pre-harvest burning (yes or no), harvest date, duration of post-harvest handling and crop yield. Crop yield for each field was determined by obtaining the weights of sugarcane on all trucks that carried the harvested cane from that field to the transfer station; this weight was then divided by the area in ha of that particular field obtained from actual field measurement using a handheld global positioning system (GPS) device. Crop duration or crop age-at-harvest was calculated from crop starting date to date-of-harvesting the crop in individual fields. Farmer interviews based on the use of a questionnaire were used for collection of much of the data.

The data collected at harvesting were CCS values for individual fields. For each field, samples of sugarcane were collected at the time of harvest. The samples were then sent for CCS determination at the laboratory of the Mitr Phol Innovation and Research Center, using the standard method for CCS measurement. Prior to harvesting, a preliminary study was conducted to examine the magnitude of within-field sampling variation of the CCS value. Two fields, each of the planted crop, the first ratoon crop, and the second ratoon crop, were selected for this preliminary study. Ten samples of three canes were taken from each field along the two diagonal lines, and were sent to the laboratory of the Mitr Phol Innovation and Research Center for CCS determination. The results indicated that the within-field sampling variation in CCS values was rather small. Means for the CCS value of the samples from the individual fields ranged from 9.70-13.90 with the standard deviations ranging from 0.50-0.96. The results suggested that a small number of samples from each field would be needed to obtain a reliable measurement of the CCS value. For this research, the limitations of time and resources allowed only 40 samples to be analyzed for CCS in a week. To cover as many fields as possible, for actual CCS measurement, two samples were taken from each field, with three canes per sample.

Sugarcane harvesting in the study village began on 1 December 2014. Sample collection for CCS determination was planned for a period of 20 weeks, with 20 fields being sampled in each week. However, in actual operation, the number of fields harvested in each week was less than 20, and in several weeks no fields were harvested.

In total, sugarcane samples were taken from 123 fields for CCS determination. The distribution of the sampled fields in the early, middle, and late milling seasons is summarized in Table 1. The weeks (W) for which data were obtained were W1, W2, W3 and W4 for the early milling season; W7, W8, W9, W11 and W12 for the mid-milling season; and W16, W17 and W18 for the late milling season.

Data on CCS values of the sugarcane in all trucks and trailers delivered to the Mitr Phu Wiang Sugar Mill throughout the 2014/2015 milling season were also obtained from the mill.

Table 1 Number of sugarcane fields harvested in the early, mid, and late milling seasons of 2014/2015

Period	Plant crop	Ratoon crop	Total
Early milling season (1/12/2014 to 14/1/2015)	15	28	43
Mid-milling season (15/1/2015 to 16/3/2015)	12	38	50
Late milling season (17/3/2015 to 31/4/2015)	5	25	30
Total	32	91	123

Data Analysis

Multiple regression analysis was used in determining the causal factors for daily variation in CCS values. The causal factors included in the analysis were: 1) land type, 2) soil type, 3) crop class, 4) harvesting date, 5) age-at-harvest (crop duration), 6) amount of fertilizer applied, 7) number of fertilizer application, 8) germination percentage, 9) number of weedings, 10) irrigation, 11) ratoon management and 12) pest and disease incidence. Others parameters were excluded from the analysis because of the low level of variation within individual parameters.

The CCS values of the individual fields were first regressed against the values of the 12 factors above to identify the factors that had a significant influence on CCS values. Then, a re-analysis was done on the reduced model, including only the significant factors. The responses of CCS to the individual significant factors were examined using simple regression analysis. For the factors that the responses appeared to be non-linear, a curvilinear regression was performed. The significant non-linear component of those factors was also included in the subsequent multiple regression analysis.

As the main focus of this study was on daily or within-day variation in CCS, the relationship between the CCS values and date of harvest was determined using simple regression analysis. The effect of time-of-harvest as determine by the regression was used to adjust the CCS values so that the adjusted CCS values were free from the time-of-harvest effect. The adjusted CCS values were calculated as follows

$$Y_{ij} = a + bX_i + d_{ij} = \bar{Y} + b\,(X_i - \bar{X}) + d_{ij}$$
$$Y_{ij}(adjusted) = Y_{ij} - b\,(X_i - \bar{X}) = (\bar{Y}) + d_{ij}$$

Where Y_{ij} and $Y_{ij}(adjusted)$ are the CCS value and the adjusted CCS value of the j^{th} field harvested on the i^{th} date, respectively; a is the constant; b is the regression coefficient of the CCS value against harvesting date; X_i is the i^{th} date at which the field was harvested; $\bar{X}$ is the mean of dates of field harvesting; and d_{ij} is the deviation of the CCS value of the j^{th} field harvested on the i^{th} date from the corresponding predicted CCS value.

The adjusted CCS values were used in the subsequent multiple regression analysis against the remaining significant factors. A sequential fit was performed using the data analysis tools of Microsoft

Excel to determine the contribution of the individual significant factors and their significant non-linear components to the daily variation in the CCS values. The relationships among the causal factors were also examined using simple correlation.

RESULTS AND DISCUSSION

Daily Variation of CCS Values Over the Milling Season

The data on CCS values of all sugarcane delivered to the Mitr Phu Wiang Sugar Mill in the 2014/2015 milling season showed a great variation, ranging from 6.4 to 17.8, with a mean of 12.9 and a standard deviation of 1.2. The CCS values of sugarcane harvested from the 123 fields at Hin Kong village in the same milling season also varied substantially, ranging from 10.5 to 18.4, with a mean of 15.1 and a standard deviation of 1.47. Figure 1 presents the CCS values over time from the two data sets. Data from the mill clearly shows an increasing trend in the CCS values until mid-April, after which the values declined toward the end of the milling season in May. However, the significant aspect of the data is the great variation in individual harvesting dates in which the gaps between the maximum and minimum CCS values were about seven units throughout the milling season. This distribution pattern was the same as that observed in previous years as well as in other mills, which was the basis for the conduct of this research.

The CCS values of sugarcane from the fields at Hin Kong village also showed a similar trend, but were on the high side of the mill data (Figure 1). This might be because of differences between the two data sets in relation to sample size for CCS determination. Each CCS value from the mill was the value of a truck-load or a trailer-load of canes which could be considered as a large-size sample (several hundred canes), while a value from a field at Hin Kong village was from the average of two small-sized samples (each comprising three canes). Nevertheless, the CCS values obtained from the fields at Hin Kong village also showed great daily variation throughout the milling season, and therefore should serve the purpose of this study. The limitation of the data from Hin Kong Village was only in relation to the shorter period of harvesting which ended at the end of March, before the declining phase of CCS values (Figure 1). However, this should not have affected the analysis for causal factors of daily CCS variation.

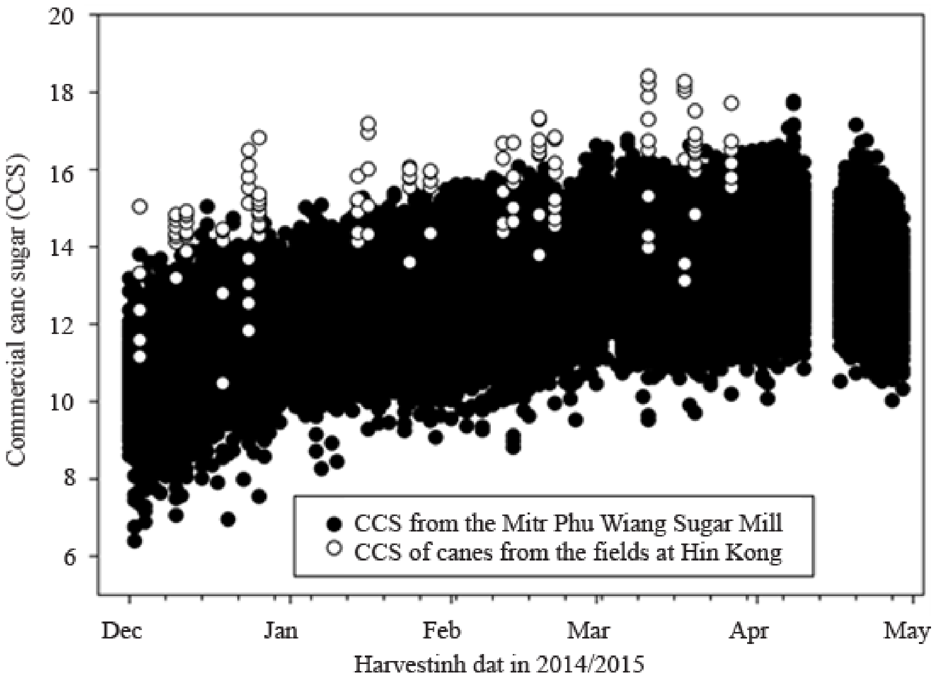

Figure 1 CCS values of sugarcane from the fields at Hin Kong village and cane from all vehicles that were processed by the Mitr Phu Wiang Sugar Mill throughout the 2014/2015 milling season

Possible Contributing Factors to CCS Variation

In this study, 12 factors were examined for their influence on CCS values of the sampled fields. These factors included: 1) land type, 2) soil type, 3) crop class, 4) harvest date, 5) age-at-harvest, 6) amount of fertilizer applied, 7) number of fertilizer application, 8) germination percentage, 9) number of weedings, 10) irrigation, 11) ratoon management, and 12) pest and disease incidence. These factors showed reasonable variation and were considered to be worthwhile for inclusion in the initial multiple regression analysis (Table 2). Others factors were excluded from the analysis because of their low variation. For example, only one sugarcane cultivar (Khon Kaen 3) was grown in the study period, and gap-filling planting was done in only a few fields.

Causal Factors for Overall CCS Variation

The results of the initial multiple regression analysis of CCS values against the 12 potential causal factors indicated that all these factors accounted for 78% of the total CCS variation. However, only three factors, i.e., harvesting date, crop class, and crop duration, showed highly significant effects on the CCS value ($P < 0.01$), while one factor (number of weedings) showed a significant influence on CCS at $P < 0.05$ (Table 3). The other factors had no significant effect on CCS, as reflected in the small differences between mean CCS values of the different classes within the individual factors (Table 2). The re-analysis with a reduced model in which only the significant factors were included showed that these four factors (harvesting date, crop class, crop duration, and number of weedings) could account for 76% of the total CCS variation (data not shown).

Table 2 Variations in possible causal factors that were included in the multiple regression analysis, and associated means and standard deviations for CCS

Factor	Description	No. of fields	Percent	Mean CCS	SD of CCS
Land type	Upland	49	39.8	15.17	1.44
	Lowland	74	60.2	15.35	1.43
Soil type	Clay	15	12.2	14.59	1.62
	Sandy	50	40.7	15.73	1.23
	Gravel	27	22.0	15.20	1.72
	Others	31	25.2	14.95	1.19
Crop class	Plant crop	32	26.0	15.94	0.97
	1st ratoon crop	22	17.9	16.19	1.07
	2nd ratoon crop	33	26.8	15.44	1.02
	3rd ratoon crop	22	17.9	14.45	1.26
	4th ratoon crop	14	11.4	13.24	1.36
Amount of fertilizer (kg ha^{-1})	157	12	9.8	14.86	2.12
	250	2	1.6	15.54	1.53
	313	40	32.5	15.24	1.28
	375	8	6.5	14.12	2.19
	500	18	14.6	14.81	0.91
	625	34	27.6	15.73	1.20
	750	5	4.1	16.44	0.74
	938	4	3.3	15.87	1.39
No. of fertilizer applications	0	0	0.0	-	-
	1	56	45.5	15.16	1.46
	2	64	52.0	15.37	1.42
	3	3	2.4	15.66	1.63
Germination (%)	100	20	16.3	15.03	1.52
	90	50	40.7	15.04	1.53
	80	23	18.7	15.67	1.30
	70	22	17.9	15.67	1.16
	60	8	6.5	15.19	1.50
No. of weedings	0	26	21.1	15.56	1.29
	1	48	39.0	14.96	1.34
	2	35	28.5	15.55	1.51
	3	14	11.4	15.15	1.71
No. of irrigations	0	108	87.8	15.21	1.41
	1	15	12.2	15.80	1.54
Ratoon management[1]	No	92	74.8	15.01	1.33
	Yes	31	25.2	16.09	1.45
Diseases and Insect pests	No	37	30.1	15.34	1.35
	Yes	86	69.9	15.25	1.47
Harvesting date	Varied from 1 December 2014 to 28 April 2015				
Crop duration	Varied from 10 to 18 months				

[1] Application of vinasse or manure, or retaining leaves and tops after harvesting.

Table 3 Regression analysis of CCS values against 12 possible causal factors

Source	df	SS	MS	F
Regression	12	196.339	16.362	33.03**
Residual	110	54.484	0.495	
Total	122	250.8223		
R Square		0.78		
Independent variable	Coefficients	Standard Error	t Stat	P-value
Harvesting date	0.025	0.002	12.091	< 0.01
Crop class	-0.471	0.062	-7.584	< 0.01
Amount of fertilizer applied	0.001	0.001	1.494	0.138
Age-at-harvest (crop duration)	-0.333	0.042	-7.974	< 0.01
No. of fertilizer applications	-0.009	0.214	-0.043	0.966
Independent variable	Coefficients	Standard Error	t Stat	P-value
No. of weedings	-0.156	0.074	-2.115	0.037
Soil type	-0.112	0.067	-1.663	0.099
Ratoon management	0.141	0.080	1.767	0.080
Land type	-0.058	0.073	-0.801	0.425
Germination (%)	-0.029	0.062	-0.467	0.641
No. of irrigations	-0.025	0.103	-0.240	0.811
Pest and disease incidence	0.134	0.140	0.959	0.340

** Significant at P < 0.01

The examination of the relationship between CCS and harvesting date indicated that the CCS value showed a continuing increase in response to the delay in harvesting (Figure 2). This relationship is well acknowledged, as it is a common phenomenon observed every year based on data recorded at the mill (Figure 1). The increase in CCS with the delay in harvesting is partly attributed to crop age, which is related to the maturation and ripening stage of the crop, and partly attributed to climate, particularly temperature and humidity. It has been well established that the CCS will continue to increase during the maturation and ripening stage of the sugarcane crop (Bull, 2000). This is amplified by high radiation, cool temperature, and dry weather, which are conductive to sugar accumulation (Glover, 1971; Legendre, 1975; Rozeff, 1993; Robertson *et al*., 1999; Kingston, 2002). These are the conditions during the winter period of the milling season in Thailand. Toward the end of the milling season, the CCS declines as the crop enters the period of hot and dry weather with short diurnal temperature range (Kingston, 2000; 2002). In the present study, crop harvesting ended before reaching the CCS decline phase. Thus, only the linear relationship between CCS and date of harvesting was observed (Figure 2). This relationship could be partially explained by crop age, as there was a significant correlation between harvesting date and crop age (r = 0.38, P < 0.01) (data not shown). However, the harvesting date could explain only 12% of the total CCS variation, and could not explain the within-day variation in the CCS values.

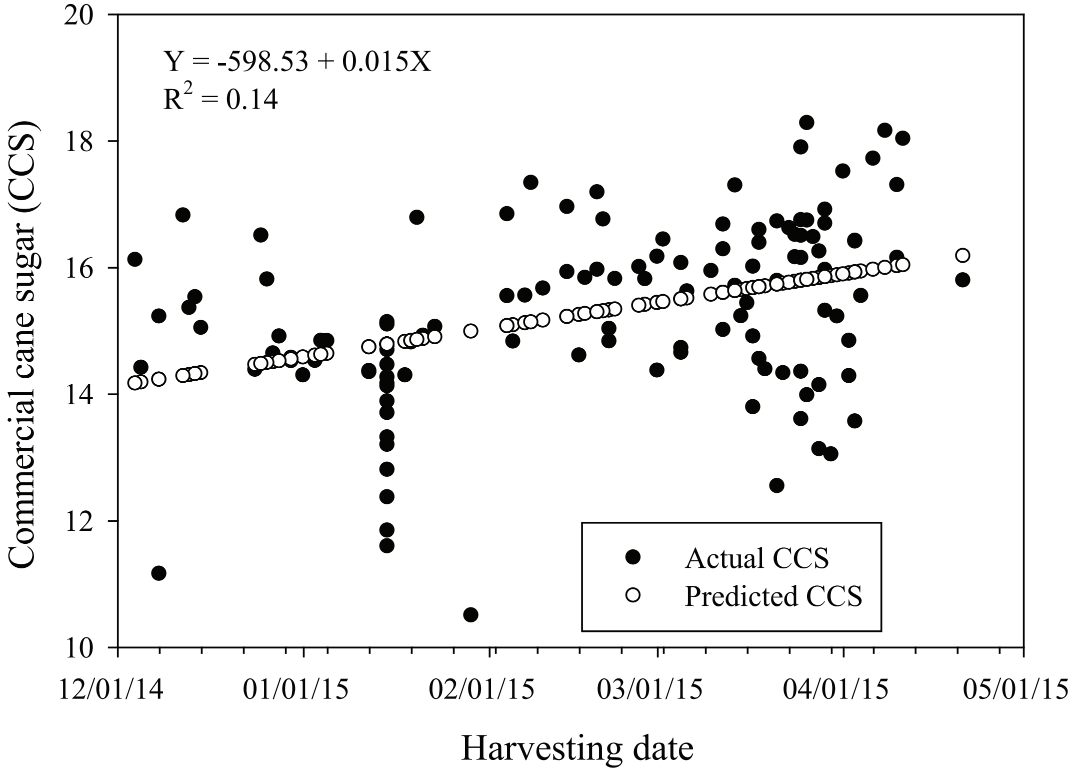

Figure 2 Relationship between CCS value and harvesting date

Causal Factors for Daily Variation in CCS

The main objective of this research was to identify the factors that cause the variation in the CCS values of sugarcane harvested on the same day (daily or within-day variation of CCS). To remove the effect of harvesting date, the CCS values were adjusted by removing the effect of harvesting date based on a regression analysis. A plot of the adjusted CCS against age-at-harvest (crop duration) showed a non-linear relationship between the two variables (Figure 3). A polynomial regression indicated significant linear and quadratic effects of age-at-harvest on CCS ($P < 0.01$) (data not shown). It can be seen from Figure 3 that the predicted CCS values were similar for crops aged between 10 and 13 months, but showed a continuous decline at an increasing rate as the crops aged beyond 13 months.

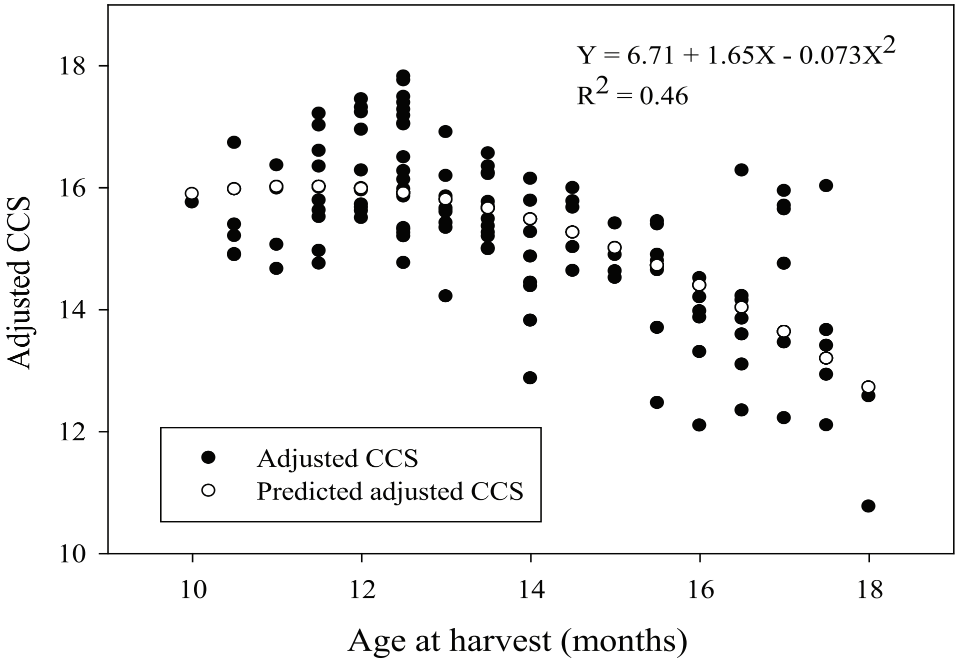

Figure 3 Relationship between adjusted CCS and age of sugarcane at harvest

The relationship between adjusted CCS and crop class was also non-linear (Figure 4). However, there was a significant negative relationship between crop class and age-at-harvest (r = -0.48, P < 0.01) but not between crop class and harvesting date (r = 0.18, P > 0.05). Thus, the effect of crop class on CCS was partially confounded with the effect of crop age-at-harvest.

The results of the sequential regression analysis of the adjusted CCS on age-at-harvest (linear and quadratic), crop class (linear and quadratic) and the number of weedings showed that only age-at-harvest and crop class were statistically significant, while the number of weedings was not significant (Table 4). The two components (linear and quadratic) of age-at-harvest accounted for 46% of the total daily variation in CCS. Including the two components of crop class added 22% more accountability of the causal factors, making them accounted for 68% of the total daily CCS variation. These results indicate that age-at-harvest (crop duration) and crop class were the two main contributing factors to the variation in the CCS of sugarcane delivered to the Mitr Phu Wiang Sugar Mill in Northeast Thailand.

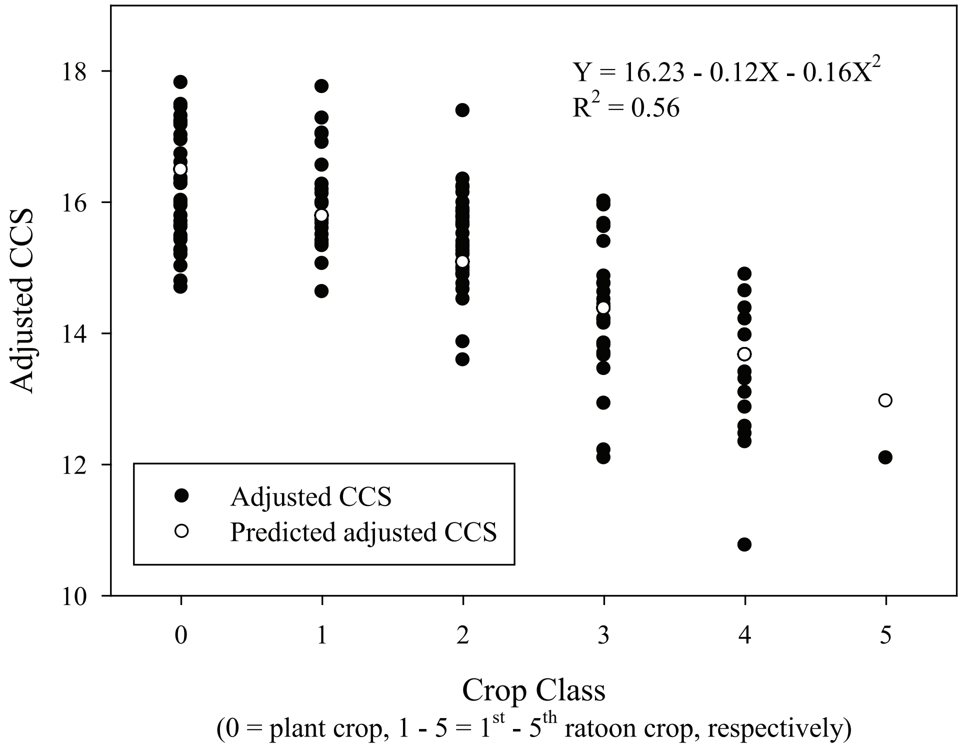

Figure 4 Relationship between adjusted CCS and cane class

Table 4 Sequential regression of adjusted CCS on age-at-harvest (linear and quadratic), crop class (linear and quadratic), and number of weedings

Source	df	MS	F	Cumulative R^2
Regression	5	29.521	51.46**	
Age-at-harvest (linear)	1	87.153	151.93**	0.41
Age (quadratic)/age (linear)	1	10.602	18.48**	0.46
Crop class (linear)/age (quadratic)	1	46.686	81.39**	0.67
Crop class (quadratic)/crop class (linear)	1	2.158	3.76*	0.68
No. of weeding/crop class (quadratic)	1	1.008	1.76^{ns}	0.69
Residual	117	0.574		

*,** Significant at $P < 0.05$ and $P < 0.01$, respectively; ns = non-significant

The results of the present study are in partial agreement with the results of a study of Tukaew *et al*. (2016) in which crop age-at-harvest and duration of cutting-to-crushing were found to be the main causal factors for the variation in CCS of sugarcane delivered to the mills in Central Thailand. Cutting-to-crushing duration had no effect on the CCS value in the present study because the values of CCS were determined at harvest with no duration for cutting-to-crushing. However, based on farmers' interviews, the cutting-to-crushing durations for all the fields in the present study were within the 24-hour allowable time of the mill. This duration has been found to have little effect on the CCS value of harvested sugarcane (Mitr Phol R&D Co., 2007).

The results of the present study also showed that, for any given harvesting date, there were fields that have great variation in the age of the sugarcane at harvest (Figure 5) as well as fields with different crop classes (Figure 6). It is acknowledged that the variations in crop age-at-harvest and in crop class within the individual harvest dates would have caused the daily variations in the CCS of sugarcane harvested at different dates. However, crop class is a factor that cannot be changed. Only age-at-harvest of the crop can be changed by changing the harvesting date of the individual fields. In addition, changing the harvesting date would address part of the crop class effect. Therefore, a way to reduce the daily variation in the CCS of sugarcane delivered to the mill would be to design and implement an appropriate harvesting plan such that all the fields would be harvested within a suitable crop age range at harvest (between 10−13 months). This would eliminate the low CCS fields due to harvesting too early or too late, and consequently raise the daily average of CCS and the overall CCS average for the milling season.

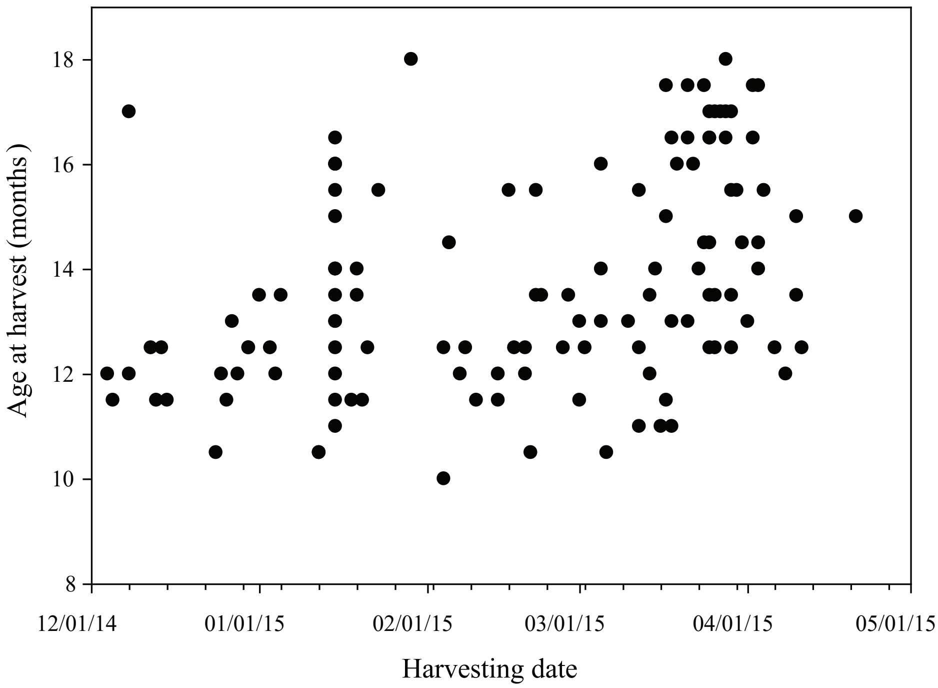

Figure 5 Age at harvest of sugarcane for different harvesting dates

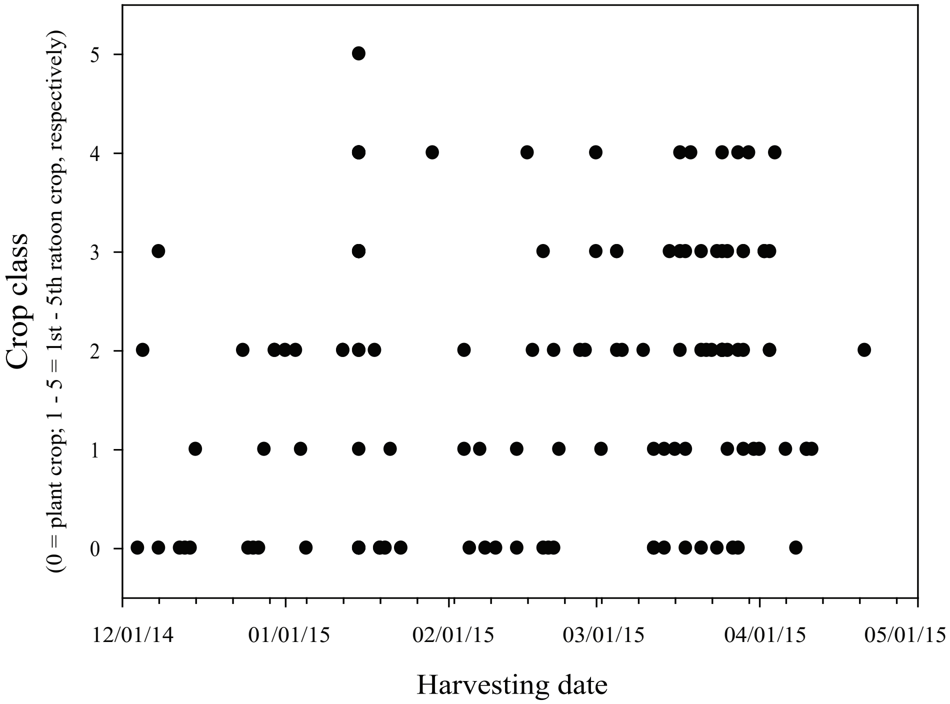

Figure 6 Crop classes of sugarcane for different harvesting dates

The importance of harvesting sugarcane at an appropriate age has long been recognized and has been the general recommendation of sugar mills to farmers in their respective service areas. The decision to harvest a sugarcane field is a complex issue, involving several parties. In most cases, farmer-owners are not the ones who make the decision to harvest sugarcane in their own fields. This is because farmers have to have a quota to deliver sugarcane to the mill on the day of harvest. Quota allocations are made by the mill in rounds during the milling season, in order to have a continuous flow of sugarcane to the mill in the quantity that is needed daily. Delivery quotas are not allocated directly to farmers, but are given to quota contractors, most of whom are large farmers in the service area of the mill. Quota contractors, in turn, allocate the quota they receive in each round to farmers who are members of their groups. These quota contractors also have their own sugarcane fields to allot a delivery quota. Some farmers may sell their sugarcane to their quota contractors before harvesting while the crop is standing in the field (pre-harvest selling). The buyers manage the scheduling of the harvest of the sugarcane in their own fields and in the fields that they buy. Thus, the decision to harvest a sugarcane field is very much in the hands of the quota contractor. In Hin Kong village, there were three quota contractors in the year that this study was conducted.

In the year of this study, through quota allocation, the Mitr Phu Wiang Sugar Mill was successful in having the daily required supply of sugarcane without long waiting times for the delivery trucks. However, the results of this study indicated that the mill did not take the age of the crop at harvest into account seriously in the quota allocations. The consequence is the great daily variation of the CCS values throughout the milling season.

This needs to be changed if the daily variation of the age of harvest of sugarcane is to be reduced. A careful harvesting plan that takes into account both the daily crushing capacity of the mill and the appropriate age of sugarcane at harvest is needed for use as the basis for allocating delivery quotas to quota contractors and farmers.

Data on planting dates and crop starting dates for the individual fields in the service area are needed to make a harvesting plan to address daily CCS variation concerns. Growth and development of the crop in each field also need to be monitored so that the latest information on the actual status of the crop in the field is available at the time of quota allocation and harvesting schedule setting. For the Mitr Phu Wiang Sugar Mill, the database of sugarcane in the individual farmers' fields has been planned, and maps of all the fields are available. It should be possible to make an arrangement with farmers to send in monthly data on the crop status of each field. Then a database management system can be developed and put in operation. Estimated yields for the individual fields are also required for designing the harvesting plan. Crop simulation models, such as APSIM-Sugarcane (Keating *et al.,* 2003) and DSSAT/Canegro (Jones *et al.,* 2003) are now available for predicting sugarcane yield in different environments and management practices. Prediction estimates by specialists should also be used. Predicted yields of the individual fields should also be a part of the database system. One important issue is by changing harvesting dates of individual fields to keep the age-at-harvest of sugarcane within a suitable range may affect the crop starting dates and the daily supply of sugarcane to the mill. In fact, making changes to harvesting dates will change the entire supply chain of sugarcane, and a new operation plan would need to be designed for the entire supply chain system.

In the near future, sugarcane harvesting will have to be done by combine harvesters, as labor to harvest sugarcane is becoming scarce. Appropriate management needs to be designed and implemented not only at harvesting but also throughout the supply chain system for combine harvesting to be effective. These involve growing, harvesting, transporting and processing sugarcane from the field to the mill (Gaucher *et al.,* 2003; Kadwa and Bezuidenhout, 2015). Combine harvesting requires synchronization of all these processes. Three key component plans for sugarcane supply chain management had been highlighted including the crop plan, the harvesting plan and the harvesting schedule (Bocca *et al.,* 2015). The crop plan optimizes the delivery of cane to the mill at the highest mill capacity. The harvest plan determines which plots will be harvested at a given time, taking into account the development of the crop in the field and the arrangements between growers and the mill. The harvesting schedule specifies the sequence of harvesting, taking into account the logistics of moving between harvesting areas with different priorities. There are various models that can be used to design these plans, including a model to support the crop plan (Grunow *et al.,* 2007; Piewthongngam *et al.,* 2009), the harvesting plan, and the harvesting schedule (Grunow *et al.*, 2007; Le Gal *et al.*, 2009; Jena and Poggi, 2013). These plans need to be designed specifically for a given mill, as each mill is unique in its historical development and its biophysical and social context (Bezuidenhout *et al.*, 2012a).

The most difficult component is the implementation of the designed plans, because there are many parties involved and mutual agreements from all parties are required. Close coordination among parties will be unavoidable for the sugar industry in the near future. Encouraging the adoption of the radical change in a complex sugarcane supply chain system requires increased participation and learning between the growing, harvesting, and milling sectors, and external support for system development and change management are also needed (Pannell, 1999; Higgins *et al.*, 2004). Management of the supply chain requires collaboration among partners in which stability, reliability, trust, personal relationships and communication are the main attributes

(Bezuidenhout *et al.*, 2012b). A willingness to share risk in order to achieve the mutually agreed long-term goals is also necessary (Sahay and Maini, 2002). To achieve these objectives will take time and continuous effort from the mill.

Changing supply chain management to achieve a suitable range of crop duration at harvest can be viewed as an initial step towards the supply chain management for combine harvesting. It is, therefore, suggested that the sugarcane processing mill should take the initiative and start implementing these changes. The crop plan, the harvesting plan, and the harvesting schedule should be initially designed with fewer restrictions than for combine harvesting. The database needs to be established and effectively managed to provide the needed information for designing and implementing the plans. An effective line of communication should be established between the mill, the quota contractors, and farmers. Participation of all parties in decision making should be organized throughout the supply chain process. Outside consultation in designing supply chain component plans and management changes should be sought as needed. The plan implementation should be closely monitored, with the results being shared with all parties. This would enforce close communication and participation among the involved parties, learning together, and building trust and commitment. If this is successful, it will prepare the involved parties to be ready for another step of the changes required in the management of the sugarcane supply chain for combine harvesting.

CONCLUSIONS

The results of this study identified age-at-harvest (crop duration) and crop class as the two main causal factors for the daily variation in the CCS of sugarcane delivered to the sugarcane processing mill under study. Reducing the differences in crop age-at-harvest to be within a suitable range would lower the daily CCS variation and raise the overall CCS mean for the entire milling season. To achieve this, management changes are needed for the entire supply chain of sugarcane. The sugarcane processing mill should take the initiative and provide strong support for implementing the proposed changes in preparation for the future use of combine harvesters. The approach being recommended based on the results of this study could potentially be used for other sugarcane processing mills, not only in Thailand but also in other sugarcane growing and processing countries.

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