EARLY-SEASON PREDICTIONS OF SUGARCANE YIELD IN FLORIDA, USA

By

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Abstract

Schedules for harvest and milling operations are initiated well in advance of the actual harvest. Yield estimates are a critical component of this planning and currently these estimates are generally based on observations by experienced scouts. This study was undertaken to supplement and to improve these yield predictions by developing a hybrid forecast scheme based on a combination of mechanistic crop modelling and empirical correlations with yield history. An early season forecast of yield (1\textsuperscript{st} May for harvesting initiated in the following November) was developed and based on the influence of temperature on leaf development of young sugarcane plants. Regression of cumulative temperature (base temperature = 10°C) for the period between 15\textsuperscript{th} January and 30\textsuperscript{th} April for 34 years from 1963 to 1996 against the subsequent yield in each season resulted in a significant correlation ($r^2 = 0.69$). A forecast made on 1\textsuperscript{st} August was based on the amount of solar radiation intercepted by the crop up to that point. Again, a significant correlation was obtained ($r^2 = 0.60$), but this later forecast was not superior to the early season forecast. Two crucial issues were identified in the analysis of these data. First, an early season frost had a large impact on yield that could be accounted for by resetting the tabulation of cumulative temperature and cumulative radiation interception to zero at the time of the frost. Second, sugarcane yields since 1998 have been substantially greater (+12.6 t/ha) than predicted from historical yields.

Introduction

The coordinated scheduling of harvest and processing are crucial for efficient operation since the Florida sugar industry is integrated vertically. Preliminary planning for the commencement of the Florida harvest in November is initiated in the preceding May with final commitments made in August. Early-season yield predictions are essential features of this advanced planning. Currently, the most reliable estimates of yield predictions are obtained by scouts who rely on direct observations and years of experience.

Yield models have been examined as possible sources of additional input to improve the accuracy of yield predictions. Generally, these models have been either empirical, relying on historical correlations between yield and various weather variables, or mechanistic where crop growth is simulated with computer software based on functions describing plant development and growth. While empirical models can establish general correlations (Allen, 1977; Alvarez \textit{et al.}, 1982), the correlations are limited to interpolations and tend to have difficulties when extrapolating to more extreme conditions. On the other hand, mechanistic models are constructed to describe the behaviour of individual plant processes contributing to crop development and growth under a wide range of conditions (Inman-Bamber, 1991; Keating \textit{et al.}, 1999). The difficulties with the mechanistic models include complexities in defining the
environment and crop variables, such that these tools are cumbersome to use and commonly need to be adjusted for each new circumstance. Furthermore, in a yield forecast mode, both the empirical and mechanistic models require assumptions about the weather conditions for the entire growing season.

This research was undertaken to explore a 'hybrid' approach, using a combination of a mechanistic framework wedded to an empirical analysis to provide early season yield forecasts. Mechanistic approaches were used to develop indices of crop status early in the season and these indices were then assessed using historical correlations between these indices and yield. Specifically, we sought to develop an early season yield prediction in May based on the potential for leaf development by the crop up to that point, and to develop a mid-season yield prediction in August based on the amount of solar radiation intercepted up to this point. These indices were correlated with mean yield ultimately recorded by the Sugar Cane Growers Cooperative for each season from 1963 to 2002.

Description of models

Early-season yield prediction

Early-season temperature was hypothesized to be critical in plant development because of the sequential nature of leaf emergence on the young sugarcane stalk. Leaf emergence was found to be linearly dependent on temperature minus a 10°C base temperature for four major cultivars grown in Florida (Sinclair et al., 2004). Small differences in the rate of leaf appearance have potential for a large influence on plant development and the amount of radiation intercepted by the crop. This is especially true in sugarcane since the crop is planted in relatively wide rows and the plants take several months to develop a closed canopy for maximum interception of radiation.

Consequently, the early-season yield prediction model was based on simply calculating for the period from 15th January to 30th April the cumulative thermal units (TU) as the sum of the mean daily temperature (mean of minimum and maximum) minus base temperature. Daily temperature data were obtained for each year from 1963 to 2002 from the weather records at the Everglades Research and Education Center (EREC), Belle Glade, FL. Historical yields reported in each season were regressed against the cumulative TU calculated for the 15th January to 30th April period preceding the harvest.

Mid-season yield prediction

The mechanistic model for the mid-season yield prediction (1st August) was expanded to be based on estimates of the amount of solar radiation intercepted by the crop up to that date. It was hypothesized that calculation of intercepted radiation, which is the basic input defining crop growth, would provide a strong basis for correlation with the yield that would eventually be harvested.

The calculation of intercepted radiation required more sophistication in the mechanistic component of the model to estimate solar radiation interception based on changing crop leaf area through the season up to 31st July.

The first challenge was to establish a weather record for incident solar radiation from 1963 to 2002. Unfortunately, incident solar radiation data at EREC proved to be reliable only for the period from 1980 to present. To take full advantage of the historical yield record from 1963, solar radiation was estimated for the period from 1963 to 1979 based on daily minimum and maximum temperature (Annandale et al., 2002).

This estimation requires a coefficient that depends on the distance from a coast. Based on analysis of recent solar radiation data, this coefficient for EREC was found to have a value of 0.205 (Gilbert, personal communication), that is consistent with a value of 0.19 given by Annandale et al. (2002) for coastal locations. Daily solar radiation predicted from this approach was well correlated ($r^2 = 0.55$) with observed values.

The correlation was improved further by comparing seven-day running means for both daily calculated and observed solar radiation ($r^2 = 0.77$). Daily incident solar radiation was calculated for each day during the 1963 to 1979 period based on seven-day running means.

The basis for calculating the cumulative radiation interception by the crop was the amount of leaf area displayed by the crop. These calculations were done based on the sequential emergence of leaves on the stalk as a function of temperature.

The TU interval for emergence of successive leaves is similar among major cultivars grown in Florida with values only varying between 97 and 108 TU (Sinclair et al., 2004). Each emerged leaf on the stalk was found to have a well-defined leaf area, although the area of individual leaves varied among
cultivars (Sinclair et al., 2004). The total leaf area on a stalk through the season was calculated simply by summing the areas of all emerged leaves. Coefficients describing the area of individual leaves for the older cultivar CP72-2086 (Sinclair et al., 2004) were initially used in these calculations.

Sugarcane plants obviously do not retain all leaves on the plant over the entire growing season. To approximate the loss in leaves, it was assumed that only the top eleven leaves remained green and active in photosynthesis. Once eleven leaves had been generated on the young plants, old leaves were removed in the tabulation of leaf area.

Since the new leaves were larger than the older leaves, the leaf area on the plant continued to increase with the emergence of new leaves.

Calculation of radiation interception from estimates of individual plant leaf area required several assumptions. Radiation interception is directly dependent on crop leaf area index (LAI) and, to obtain this estimate, it is necessary to multiply plant leaf area by the population density of stalks.

It was assumed that there were 10 main stalks/m² involved in the effective radiation interception during the early stages of crop growth. If additional information is available to predict stalk population density, this assumption can be altered.

The fraction of incident radiation intercepted by a closed leaf canopy has been documented to be an exponential function of LAI. Increasing LAI results in an increase in radiation interception, which is well described for a random distribution of leaves by an extinction coefficient of approximately 0.5.

During the early stages of sugarcane growth, however, wide rows cause leaves to be clumped in rows so the assumption of random leaf distribution is not met. Sinclair and Lemon (1974) found with maize that the influence of leaf clumping in rows could be described by decreasing the effective leaf area for radiation interception as an empirical linear function based on leaf area.

Their approach was incorporated into the exponential function to calculate intercepted radiation (R) from incident radiation (I) when LAI<4.0.

\[ R = 1 \times (1 - \exp(-0.5 \times (0.4 + 0.15 \times \text{LAI}) \times \text{LAI}) \]  

The mid-season mechanistic model was based on the summation of R based on LAI and incident radiation for each day from 15th January through 31st July. Cumulative R was regressed against historical yields for each year.

Results and discussion

Early-season yield prediction

There was a significant overall trend between yield and cumulative TU for the period from 15th January to 30th April. However, there were two distinct groups of years that did not conform to the overall trend. One group had low yields even though cumulative TU was high and the second group had exceptionally high yields.

The seasons that had apparent low yields were found to be ones that had a freeze during this winter period. Assuming that the freeze killed the existing leaf area, the computation of cumulative TU was reset to zero at the freeze and a new, lower cumulative TU was calculated.

While this re-computation caused the seasons with a freeze and low yield years to conform to the overall trend, the use of a general criterion for a freeze of minimum temperature less than 0°C caused several seasons with moderate yields to have re-computed cumulative TU that were inconsistent with their high yields.

We speculated that the critical criterion for resetting the computation of cumulative TU was whether a frost developed when the temperature was less than 0°C that killed existing leaves. Assuming that a high atmospheric dewpoint may have been necessary to result in frost, an additional criterion for identifying frost was that the minimum temperature on nights before and after the freeze must have a minimum temperature greater than 3.5°C as an indicator of a humid air mass allowing frost.

This relatively simple approach caused the exceptional years with low yields to be consistent with the overall yield trend but did not inhibit the accumulation of TU in other years (Figure 1).

The second group of exceptional data existed in years since 1997 in which yields were substantially greater (mean of +12.6 t/ha) than the overall trend based on cumulative TU. The basis for this dramatic increase in yields is not known, but there have been management and genetic improvements that need to be explored as possible explanations.
One recent management change has been the application of calcium silicate slag to more than 40,000 ha of organic soils used in sugarcane—rice rotations during the period from 1990 to 2003. Calcium-silicate slag use in Florida has been shown to significantly increase sugarcane tonnage, with a residual effect lasting for several ratoon crops (Elawad et al., 1982; Alvarez et al., 1988; Anderson et al., 1991).

Genetic improvements may include the increased use of new, higher-yielding clones such as CP80-1743, CP88-1762 and CP89-2143. These three clones occupied only 12.8% of the EAA acreage in 1997, but have spread to 42.5% of the 2003 acreage (Glaz and Vonderwell, 2003).

The regression results for the long-term historical relationship between yield and cumulative TU, excluding the recent high-yield years, indicated a yield increase of 1.43 t/ha for every 100 TU increase. The $r^2$ for this regression was 0.69 and the standard deviation of the regression was only 2.69 t/ha.

Mid-season yield prediction

The initial graph of yield as a function of cumulative R through 31st July again showed the two divergent groups of years as discussed above. The effect of frost was handled as described above, in that cumulative R was reset to zero following a frost. The recent, high-yielding years were removed from the regression analysis. Consequently, there was a clear trend between increased yields and increased cumulative R (Figure 2).

The effort to calculate potential crop growth through mid season based on intercepted R did not improve upon the yield predictions of the early-season model. The model based on R interception through 31st July had an $r^2 = 0.60$ and a standard deviation of 3.03 t/ha.

On the other hand, the incorporation of cultivar-specific variables defining the area of individual leaves allowed an assessment of the possible benefit that may have resulted from alteration of these traits in modern cultivars.

Cumulative R was recomputed for recent years based on the coefficients defining leaf area for the more modern cultivar CP88-1762 (Sinclair et al., 2004).

Consequently, the cumulative R for the newer cultivar was increased and shifted these data to the right when graphed with yield (Figure 2).
Cumulative Intersect Radiation (MJ m⁻²)

Fig. 2—Mean cane yield for each season since 1963 regressed against cumulative intercepted radiation from January 15th to 31st July.

These results indicate that at least part of the explanation for the recent increase in yields in Florida may be a consequence of the use of a newer cultivar with larger early leaves. Yields in recent years, however, are still much greater than expected for the overall response trend to cumulative R indicating additional factors seemingly contributed to the yield increase.

Conclusions

This study was unique in that it attempted to create hybrid models that were based on mechanistic understanding of sugarcane development and growth and then these were used to generate within-season yield forecasts using historical empirical relationships. This approach worked well for most years of the data sets. Surprisingly, the early-season yield prediction based solely on cumulative TU through 30th April was superior to the model based on intercepted radiation through 31st July.

Two of the more important conclusions of this modelling effort resulted from the identification of years that deviated substantially from the long-term historical yield response. First, this analysis quantified the importance of frost during early crop development on subsequent yield. Second, this analysis highlighted the dramatic increase in yields that has occurred in recent years. Certainly, research needs to focus on the explanation for these yield increases and develop approaches to incorporate this understanding into yield forecast models.

REFERENCES


PRÉVISIONS PRÉCOCES DES RENDEMENTS DE CANNE À SUCRE EN FLORIDE, ÉTATS UNIS

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MOTS-CLÉS: Modèle De Rendement, Température, Rayonnement Solaire, Développement Foliare.

Résumé

La planification de la récolte et des opérations de l’usine est faite bien avant le début même de la récolte actuelle. Les estimations de rendement jouent un rôle essentiel dans cette planification et sont actuellement basées sur des prévisions faites par des observateurs expérimentés. Cette étude a été entreprise pour compléter et améliorer ces prévisions de rendement en développant un système de prévision mixte, reposant sur une combinaison d’un modèle mécaniste de rendement et sur des corrélations empiriques établies à partir de l’historique de rendement. Une estimation du rendement en début de récolte (le 1er mai pour une moisson à être effectuée en novembre prochain) a été conçue et fondée sur l’influence de la température sur le développement foliaire des jeunes plants de canne à sucre. Une régression de la température cumulée (température de base = 10°C) pour la période entre le 15 janvier et le 30 avril pendant 34 années (1963 à 1996) sur le rendement subséquent pour chaque saison a produit une corrélation significative ($r^2 = 0.69$). Une prévision fait le 1er août à partir de la quantité de rayonnement solaire intercepté par la canne jusqu’à cet instant a donné encore une fois une corrélation significative ($r^2 = 0.60$), mais cette dernière prévision n’était cependant pas meilleure que celle du début de saison. Deux aspects cruciaux sont apparus durant l’analyse des données. D’abord, un gel en début de saison a eu un gros impact sur le rendement; cet effet pourrait être pris en compte en remettant à zéro la tabulation de la température cumulative et l’interception cumulative de rayonnement à l’heure du gel. En seconde lieu, les rendements de la canne à sucre depuis 1998 ont été bien plus élevés (+12.6 t/ha) que ceux prévus à partir de la méthode utilisant les rendements historiques.

Resumen

La planificación de las operaciones de cosecha y molienda se inician bien adelantadas a la cosecha venidera. Los estimados de campo son un componente crítico de esta planificación y actualmente estos estimados son basados en observaciones por personas con esta experiencia. Con el fin de mejorar y complementar estas predicciones de rendimiento de campo se llevó a cabo este estudio con el fin de desarrollar un esquema híbrido de pronóstico basado en una combinación de modelar la cosecha futura con una correlación empírica histórica. Se desarrolló un pronóstico de rendimiento de campo a temprana edad (1 de Mayo, precediendo la cosecha que se inicia en Noviembre) basado en la influencia de la temperatura en el desarrollo foliar de plantas jóvenes de caña de azúcar. Una regresión de temperatura acumulada (temperatura base = 10°C) para el período comprendido entre el 15 de Enero y el 30 de Abril durante 34 años, desde 1963 hasta 1996, contra el rendimiento subsiguiente para cada cosecha resultó en una correlación altamente significativa ($r^2 = 0.69$). Una predicción hecha el 1 de Agosto fue basada en la cantidad de radiación solar interceptada por el cultivo de la caña hasta ese momento. De nuevo, se obtuvo una correlación alta ($r^2 = 0.60$) pero esta última predicción no fue superior a la predicción hecha temprano en la temporada. Dos puntos cruciales fueron identificados en el análisis de estos datos. Primero, una helada temprana tuvo un gran impacto sobre el rendimiento del cual se pudo dar cuenta ajustando la tabulación de la temperatura acumulada y la radiación interceptada acumulada a cero al momento de la helada. Segundo, los rendimientos de la caña de azúcar desde 1998 han sido sustancialmente más altos (12.6 t ha$^{-1}$) que los rendimientos estimados históricos. El manejo del cultivo y el mejoramiento genético que fueron responsables por este incremento en el rendimiento están siendo investigados.