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Understanding Sugarcane Yield Gap and Bettering Crop Management Through Crop Production Efficiency

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1. Introduction

The comparison among farming systems and regions would improve the understanding of how and what driving factors explains the crop yield variability over time and space. Very often, however, farm managers and policy makers fall in difficult to establish reliable indexes to compare farming systems plots and regions. Having a quantitate index, we could derive relationships regarding climate, soil and socioeconomic, as well as to determine which factors contribute or hinder the development in a given region and time.

Monteith (1977) suggested agroecosystems as machines that utilize solar energy to maintain composition and organization. From a thermodynamic standpoint, the efficiency of any process can be expressed as the ratio of energy output to energy input. Since the 1970s, this concept has been applied to analyze the energy flow in agroecosystems, as well as to analyze the relation between biomass chemical energy and incident solar radiation.

We could apply this approach to understand the regional agricultural development and crop yield gap, once it could elucidate biophysical factors, such as the pedoclimatic conditions, affecting crop yields at a local scale. However, for a broader evaluation, one should also include structural components, corresponding to the agricultural systems and management practices adopted; institutional effects, involving governmental actions affecting price, credit, commercialization, and incentives; and research and development, related to innovations to increase yield and solve problems that restrict agricultural-related activities (Carvalho, 2009).

Also, to make this approach useful in an operational way, one could assume crop efficiency such as a quantitative indicator, helping to compare and evaluate in time and space, the farming development level. The efficiency of crop production can be assumed as the ratio between observed and attainable crop yield (Marin et al., 2008).

In order to evaluate the effectiveness of this tool, the concept of crop efficiency was applied to study the sugarcane performance in the State of São Paulo, Brazil, the main region of this crop production, representing approximately 60% of the total Country's sugarcane production (IBGE, 2002).

2. Methods and input data

The weather data had been supplied by the Brazilian Agrometeorological Monitoring System (EMBRAPA INFORMÁTICA AGROPECUÁRIA, 2002), comprising the period between 1990 and 2006. The weather data was organized in a 10 day time step. Daily solar radiation values were simulated using the Bristow and Campbell (1984) method previously calibrated using A=0.7812, B=0.00515, and C=2.2 as model parameters.

An empirical model derived from Doorembos & Kassan (1979) was used to assess the potential (PY) (Equation 1) and attainable water limited yield (WLY) as proposed by Jensen (1968) (Equation 2).

$$PY = -6.2501 + 0.2187\ S + 0.3304\ T \quad (\text{t ha}^{-1}\ 10\ \text{day}^{-1}) \tag{1}$$

where T is the mean air temperature (°C) for 10 days and S is the incident solar radiation (MJ m^{-2} d^{-1}).

$$\frac{WLY}{PY} = \left(\frac{ETa_1}{ETm_1}\right)^{\lambda_1} \left(\frac{ETa_2}{ETm_2}\right)^{\lambda_2} \left(\frac{ETa_3}{ETm_3}\right)^{\lambda_3} \tag{2}$$

where λ_1=0.43, λ_2=0.39, and λ_3=0.07 are water deficit sensibility factors for each of the three crop phases, such as: 1) initial, from planting to 30 days after (DAP), 2) crop development, up to 330 DAP, and 3) late, up to 365 DAP.

The actual crop evapotranspiration (ETa) was computed for a 10 day time step using a simple crop water-balance simulation (Thornthwaite & Mather, 1955). The Kc coefficients and development stages used were described by Doorembos & Kassan (1979) (Table 1) and available soil water was chosen according to Smith et al. (2005). Reference evapotranspiration (ETo) was estimated following Camargo et al. (1999), which was modified from Thornthwaite (1948) to match with Penman-Monteith method (Allen et al., 1998) using just air temperatures as input weather data.

Crop coefficients were obtained in Doorembos & Kassan (1979) by assuming a 12 months growing cycle, using the adjustments provided by Barbieri (1993). The simulations were done for three growing seasons (May to April, July to June, and October to September) representing the typical ratoon crop in early , middle and late growing seasons. The results from each year were averaged, and the average was used as a reference yield to efficiency calculation.

Actual sugarcane yield values (AY) for each county of the São Paulo State during the growing seasons of 1990-1991 and 2005-2006 were obtained from the Brazilian Institute of Geography and Statistics (IBGE) (www.sidra.ibge.br). Both AY and WLY dataset were spatially organized and their maps were generated by ordinary kriging interpolation tool in ArcGIS 9.3 (ESRI, Redlands, CA), using a 900 m spatial resolution grid.

The soil fertility was taken into account in the empirical model through a soil correction factor (SCF) varying from 0,74 to 1 (Table 1) based on Prado (2005), who classified the soils State of Sao Paulo considering their suitability for sugarcane production. In that classification, Prado (2005) states four yield ranges for sugarcane. The values presented in Table 1 mean the normalized values of those yield ranges. To apply this concept for the State of Sao Paulo, the soil map of the State was re-classified using the criteria suggested by Prado

(2005). Using the raster calculator tool available in ArcGIS 9.3 (ESRI, Redlands, CA), the SCF maps were multiplied by WLY maps to produce a map of soil and water limited yield (SWLY) for every growing season.

Aptitude	soil correction factor
Good	1.00
Regular	0.94
Restrict	0.84
Inadequate	0.74

Table 1. Soil correction factor (SCF) for sugarcane in the State of São Paulo.

In order to obtain the sugarcane efficiency maps for the State of Sao Paulo, those AY maps were divided by AY maps using the raster calculator tool in ArcGIS 9.3 (ESRI, Redlands, CA). This procedure had been repeated for every season, resulting in a set of 16 efficiency maps.

To quantify the soil and sugarcane production efficiency (SPE) relationship, soil aptitude classes were converted into a numerical rank from 1 to 4 and the Spearman Rank Correlation (SRC) coefficient (Snedecor & Cochran, 1982) was applied. To correlate efficiency with the others variables – air temperatures, rainfall, water deficit and solar radiation– the Pearson method (PC) was used (SNEDECOR; COCHRAN, 1982). Socio-economic (SE) influences on SPE, as well as the influence of crop management (varieties, diseases, pests etc.) was assumed to be the complimentary value to the sum of correlation indexes regarding soil and climate variables (Equation 3).

$$SE = 1 - SRC - PC \quad (3)$$

3. Sugarcane crop efficiency in the state of Sao Paulo

Sugarcane is one of the world’s major food-producing C4 crops, providing about 75% of world sugar harvested for human consumption (Souza et al., 2008) and one of the most important crops for the Brazilian economy. More recently, sugarcane has also become recognized as one of the central plant species for energy production as liquid fuel and electricity (Goldenberg, 2007). Biofuels are, at present, the fourth source of primary energy after oil, coal and gas. Brazil is the world's largest exporter of ethanol and the world's second largest producer, the US being the largest. In 2006 Brazil alone produced 16.3 billion liters, 33.3% of the world's total ethanol production and 42% of the world's ethanol used as fuel, and from then on ethanol production increased from year to year. Particularly in the US, Brazil, the EU and some Asian countries, government-led incentive programs focus on renewable sources of energy. The main driver behind these recent efforts to increase the volume of biofuels in the energy mix are concerns over climate change and greenhouse gas (GHG) emissions (primarily CO_2), and widely fluctuating oil prices with the desire to diversify and stabilize energy supplies. In addition to the commercial uses for sugar, ethanol and electricity in mills, the crop is widely used by small farmers around the country as feedstock for animals or as raw material for homemade rum and brown sugar.

The overall SPE average for the State of Sao Paulo was 48%, increasing from 0.42 to 0.57 throughout the analyzed period. Between 1990/1991 and 1995/1996, the SPE oscillated around 0.45 as a result of the tough macroeconomic conjuncture experienced by Brazil at that period, as well as due the unfavorable conditions for sugar and ethanol commercialization (GOLDEMBERG et al., 2007). However, an expressive yield increase has occurred in the last 6 years of the time series (Figure 2), as a result of the increased ethanol consumption in Brazil. This, in turn, was a consequence of better gasoline-ethanol price ratio since the beginning of the 2000s, and the availability of bi-fuel vehicles in Brazil after 2002 (Macedo, 2007).

Along the analyzed period, the average yield of the State of Sao Paulo increased 12 t ha^{-1} (Figure 2). Based on this, we derived that for each SPE percentage point increased there was a rise of 0.8 t ha^{-1}. Extrapolating it for the current sugarcane growing area in the State of Sao Paulo, it would represent an increase of 2 million tons of cane per each percentage point. This number takes especial importance when discussing the expansion of Brazilian sugarcane growing area (Manzatto et al., 2009), meaning that by driving new investments to zones with higher SPE, less land would be needed to supply the Brazilian and international sugar and ethanol demands.

The SPE maps showed northern and central region as the areas where SPE had the higher increase rates as a consequence of the new mills installed in those regions during this decade (Figure 3). High SPE areas (>80%) showed the higher expansion along the time (Figure 3d and 3e), while low SPE (<20%) were reduced in about 30% (Table 3, Figure 3b e 3c).

Areas with SPE higher than 80% expanded from 17610 km^2 to 68754 km^2 (Table 3), denoting the intensification of land use in the State of Sao Paulo and new production pattern in sugarcane fields. In the traditional areas growing sugarcane, where SPE is normally higher, this process may be a consequence of the use of better crop management mainly through varieties, fertilizers, and harvest management (Figure 3k, 3o and 3p).

In the newer areas, where SPE is lower, the SPE increase seems to be a consequence of the replacement of non-commercial sugarcane areas, used for animal feeding and home uses, by the commercial ones (sugar mills oriented), as sugar mills had expanded to those regions and had incorporated an important land amount to the sugarcane production system. This occurred mostly after 2002 and the SPE increasing trend seems to be a consequence of the investments applied to get suitable lands for sugarcane production.

In order to identify the relative importance of SPE drivers, we found climate as responding for 43% of spatial variability of SPE, while soil responded for 15% (varying from 10% to 18%) of the SPE variability, as an overall average across spatial and time scales. Therefore, the soil plus climate related factors responded for 58% of total SPE variability (Table 4), from which we derived that biotic, management and socio-economic factors together explained up to 42% of SPE variability.

Breaking the climate determination coefficient up into its components, we found solar radiation as the most important factor, followed by water deficit, maximum temperature, rainfall and minimum temperature (Table 5). Solar radiation as the higher determination coefficient variable may be due to the fact of most of the sugarcane growing areas have occupied some of the best agricultural areas of the State of Sao Paulo, where yield limiting factors have less influence. Thus, the crop was able to respond to a potential yield related variable, such as solar radiation (Bowen & Baethgen, 2002). In spite the inclusion of new areas at the west of the State of Sao Paulo, this has occurred just in the last few years, minimizing its impact into the analysis.

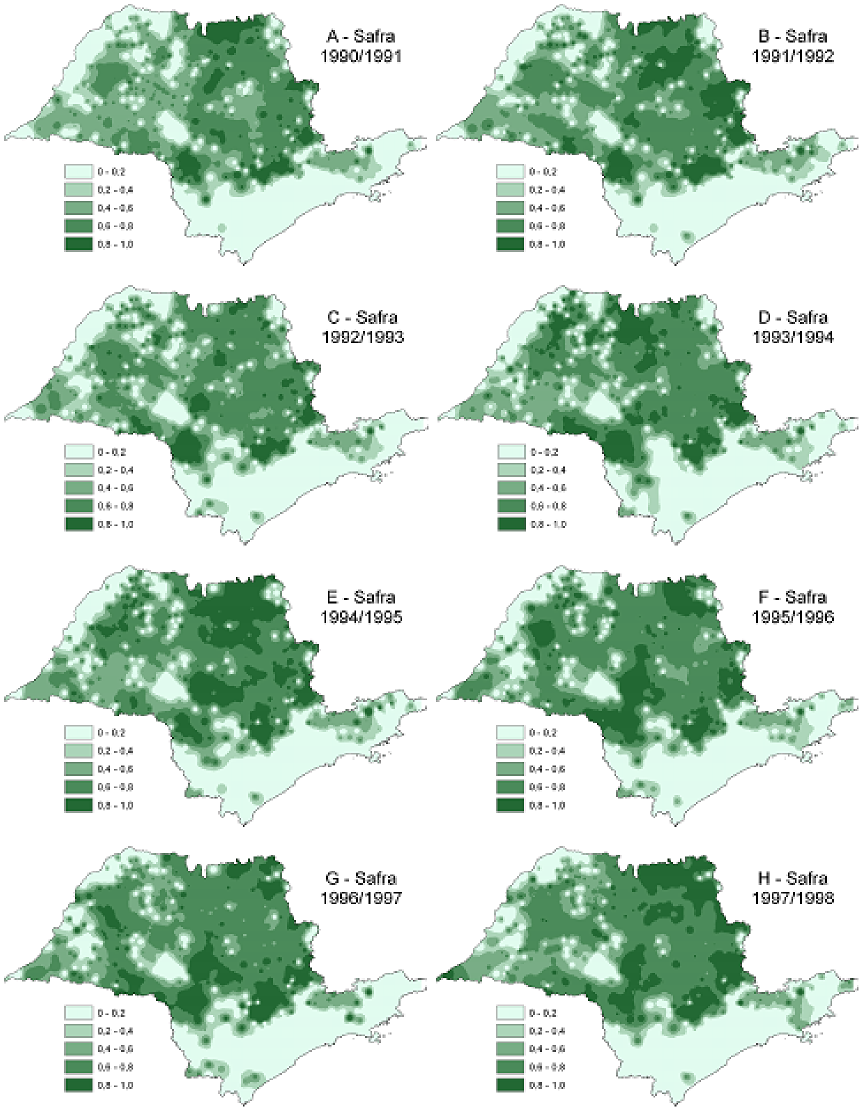

Fig. 1. Sugarcane production efficiency in the State of Sao Paulo from season 1990/1991 to 1997/1998.

Water deficit explained 12% of SPE variability, once rainfall amount and distribution seems to be enough to assure certain levels of sugarcane yield even in the worst years along the time series herein analyzed. Even in the western of Sao Paulo, where water deficit usually gets higher than other regions, the sugarcane yield still variation within a high yield range. However, we may infer that the same analysis including higher water deficit locations would certainly result in a higher R^2 for water deficit.

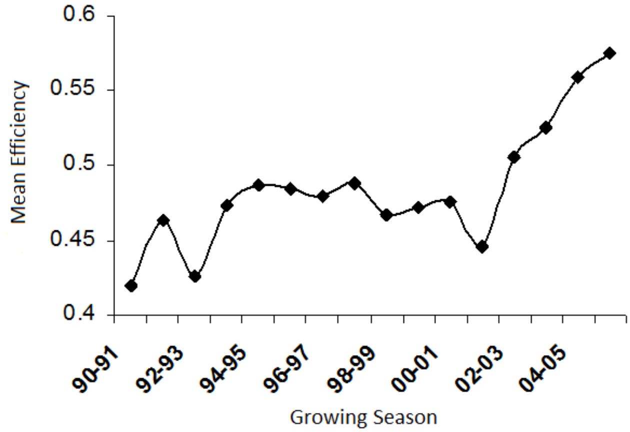

Fig. 2. Time variation of sugarcane production efficiency in the State of Sao Paulo between seasons 1990/1991 and 2005/2006.

Efficiency Class	**Growing Season**							
	90/91	**91/92**	**92/93**	**93/94**	**94/95**	**95/96**	**96/97**	**97/98**
0 – 0.2	74369	68163	75092	67202	65013	65226	67059	66000
0.2 – 0.4	31141	28129	32060	31230	29030	29086	26558	24244
0.4 – 0.6	60006	50706	48556	44223	42757	35303	37199	38015
0.6 – 0.8	65083	72108	76701	76103	67343	85220	86557	81450
0.8 – 1.0	17611	29103	15801	29451	44066	33374	30836	38501
Efficiency Class	**Growing Season**							
	98/99	**99/00**	**00/01**	**01/02**	**02/03**	**03/04**	**04/05**	**05/06**
0 – 0.2	67847	69055	76600	77018	66247	64055	60851	57088
0.2 – 0.4	23441	24970	25011	28593	23059	23037	19050	18367
0.4 – 0.6	47039	36473	31311	36012	39253	33010	23628	23083
0.6 – 0.8	90020	87013	72275	86085	80225	77207	79900	80916
0.8 – 1.0	19862	30699	43012	20501	39425	50900	64780	68754

Table 3. Sugarcane production efficiency area distribution classes (km^2) in the State of Sao Paulo from season 1990/1991 to 2005/2006.

Driver factor	Determination Coefficient
Climate	0.43
Soil	0.15
Total	0.58

Table 4. Average determination coefficients between climate and soil variables with sugarcane production efficiency in the State of Sao Paulo from season 1990/1991 to 2006/2007.

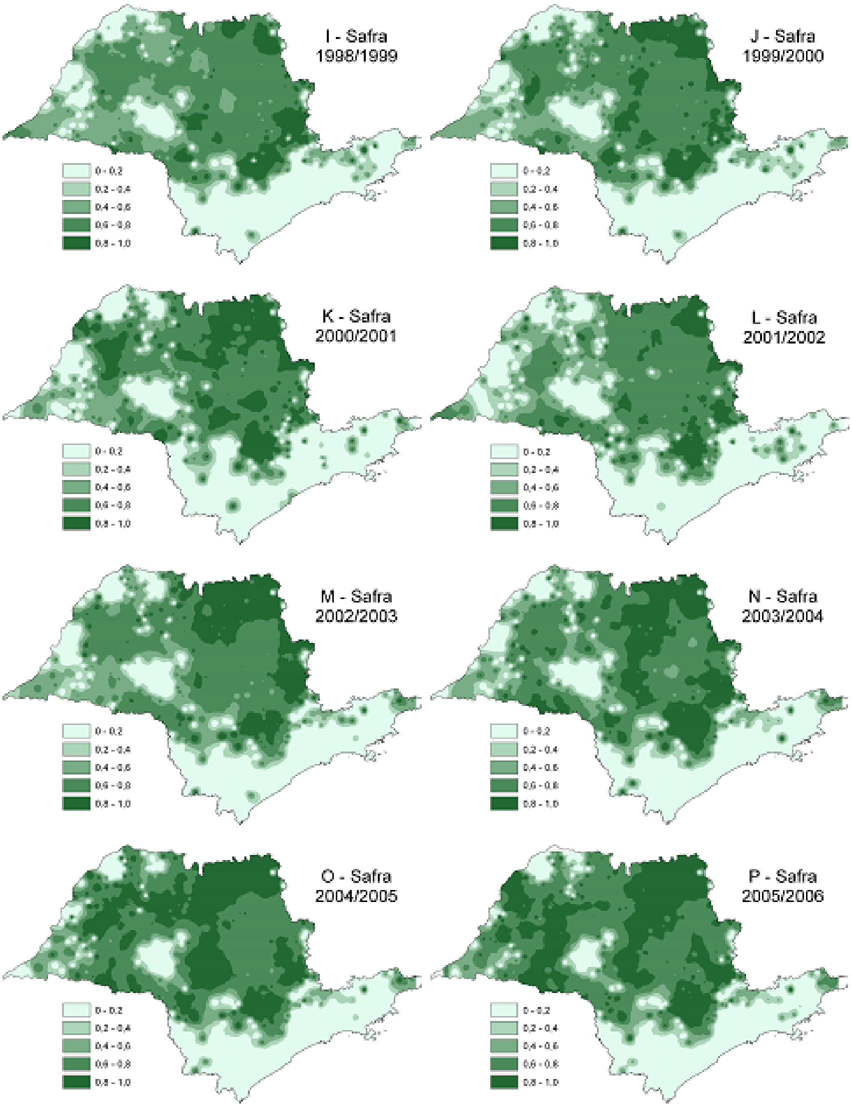

Fig. 3. Sugarcane production efficiency in the State of Sao Paulo from season 1998/1999 to 2005/2006 (continuation).

Variable	R^2
Solar radiation	0.16
Water deficit	0.12
Maximum temperature	0.08
Rainfall	0.06
Minimum temperature	0.01
Total	0.43

Table 5. Average Pearson coefficient (R^2) from season 1990/1991 to 2005/2006, for solar radiation, rainfall, water deficit, maximum and minimum temperature.

The aggregation of climatic data into 10 day time step should be also considered as it has reduced time variability associated climatic variables. Also, matters to remember that analysis were based on growing season time-step average, and this really eliminated almost temporal variability. Thus, additional to the reasons discussed for water deficits, the results obtained for rainfall and temperatures seem to be related with data aggregation, as most of the time variability has been diluted by averaging the values over time.

The remaining 42% explaining the non-abiotic SPE drivers may be time-related to public policies, prices, and costs, mainly. Management and genetic improvements are also included in the amount, but in general the signals due to such factors are better expressed using a constant increasing rates, rather than a variable cause affecting yields.

By comparing fertilizer consumed and the Spearman index we intended to explore the effect of soil management on SPE (Figure 4). For this evaluation we hypothesized that seasons under tough economic conditions for growers should show higher correlation between soil and SPE. In opposite, when economy had been favorable to sugarcane business, lesser correlation between soil and SPE would be expect, since the fertilizer application reduced the fertility deficiencies in poorer soils, masking soil spatial variability.

For the period between 2002/2003 and 2005/2006, both Spearman and consumption of fertilizers have increased, contradicting the hypothesis just postulated. It may be due the intensive expansion of sugarcane growing areas to the west of the State of Sao Paulo, occupying less fertile soils than the traditional areas and thus increasing the importance of soil to explain SPE variability.

Thus, assuming that the hypothesis addressed before as correct, we can expect the SPE-soil correlation to fall in the coming years, since new the soil fertility of those new areas would be gradually improved over time, as can be observed after 2004 (Figure 4).

Since 2004, the State average observed yield reached 50 t ha^{-1} spread over a wider area of the State of Sao Paulo. At the same time, the average attainable yield was 93 t ha^{-1} in such a way that SPE was 0.52 in 2003/2004, 0.56 in 2004/2005 and in 0.57 during 2005/2006 growing season. At the same time, sugar price rose from US$ 11.3/50kg to US$ 20/50kg in just 1 year, seems to be related to that strong increase in SPE. The sugar price-SPE correlation analysis resulted in R^2=0.53 showing a high influence of the commodity prices to explain the SPE. Interesting to remember sugar prices being self-correlated with climate variables in Brazil, as Brazil in the largest producer in the world, and that is why sugar price-SPE R^2 had a value higher than 0.42 as it should be expected.

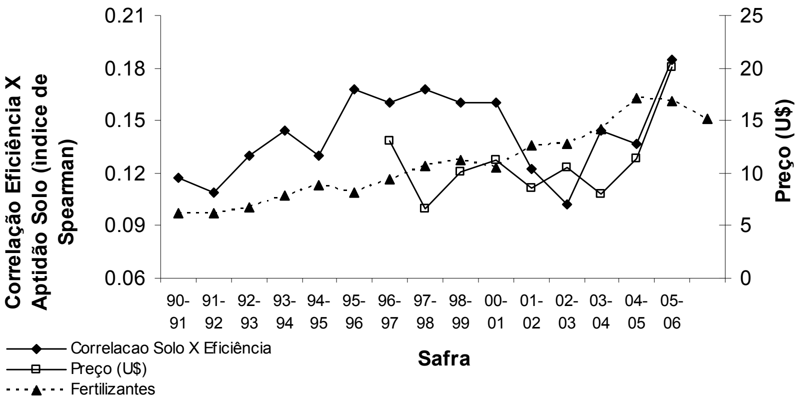

Fig. 4. Sugar prices (U$ per 50kg), commercialized amount of fertilizers in Brazilian central region (10^9 tons) after Ferreira & Gonçalves (2007) and average sugarcane production efficiency in the State of Sao Paulo.

4. Conclusion remarks

The sugarcane crop efficiency increased from 0.42 to 0.58 throughout the period from 1990 to 2006. The efficiency class above 80% showed the higher increase rates along that period. The crop yield gap has been reduced from 58% to 42%, possibly indicating the effect of the adoption of new technologies and the expansion of new mills in the west of the State of São Paulo.

The main abiotic variable explaining the sugarcane crop efficiency was the solar radiation (R2=0.16). All climate elements together explained nearly 43% of SEP variability. In average, 15% of SEP variability was explained to soil variability, with two different patterns: one from 1990 to 2001 and another from 2002 to 2006.

Adding climate and soil factors, we got biotic factors explaining 58 of SEP variability. It implies that 42% of SEP variability were explained by others factors, such as sugar prices.

5. Acknowledgements

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