# CROP PRODUCTION EFFICIENCY OF SUGARCANE IN THE STATE OF SÃO PAULO: I. CLIMATE AND SOIL ASPECTS

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ABSTRACT: A concept of crop production efficiency was derived from thermodynamic efficiency in order to generate a tool for performance evaluation of agricultural systems at local or regional scales. In thermodynamics, efficiency can be calculated by the ratio between output and input energy employed in some process, and to establish the agricultural-thermodynamic analogy, the input energy to realize some biological process was represented by potential (or maximum) crop yield assessed through any model based on environmental variables that affect crop development – the FAO agroecological method zone were applied here. The real crop yield, observed in commercial field conditions or tabulated at a county scale by national statistical services was considered as the available energy fixed in the bioconversion process. This paper intends to estimate the maximum and real sugarcane yields and to generate crop efficiency maps for the State of São Paulo, analyzing how much climate and soil may explain the spatial variability of sugarcane efficiency.
KEY-WORDS: climate, soil, spatial modeling.

RESUMO: Um conceito da eficiência da produção agrícola foi derivado da termodinâmica com o objetivo de produzir uma ferramenta para a avaliação de desempenho de sistemas agrícolas em escalas locais ou regionais e de descrever os fatores que influem em seu desempenho. Em termodinâmica, a eficiência pode ser calculada pela relação entre energia resultante de um processo e o total de energia utilizado para sua consecução. Por analogia entre agricultura e a termodinâmica, a energia da entrada do processo foi substituída pela produtividade potencial (ou máxima), computada através de modelo baseado em variáveis ambientais que influem sobre o desenvolvimento da cultura. Neste artigo, utilizou-se o método das zonas agroecológicas da FAO Como energia de entrada e o rendimento real da cultura, observado em condições de campo ou tabulado em escala municipal pelos institutos de estatística, foi considerado como a energia resultante do processo de bioconversão. Este trabalho teve por objetivo gerar mapas de eficiência para o Estado de São Paulo e analisar qual a importância relativa do clima e do solo na variabilidade espacial da eficiência no Estado de São Paulo.
PALAVRAS-CHAVE: clima, solo, modelagem espacial.

INTRODUTION : Ecosystems can be compared to machines that use the solar energy to remain themselves organized. From the thermodynamics, the efficiency of any process can be expressed by the ratio between useful energy and available energy to realize the process. This concept has been applied to analyze the energy flow in agro-ecosystems since the 60´s years (Holiday, 1966; Monteith, 1972; Monteith, 1977; Kiniry et al., 1989; Awal & Ikeda, 2003;

Albrizio & Steduto, 2005; Steduto & Albrizio, 2005) and normally make relations between biomass chemical energy and solar radiation.

Monteith (1972) suggests that this approach could be also applied to improve the understanding of biophysical factors that intervene with the crop yield. Pinazza (1985) listed four basic factor that affect the regional agricultural development: physical, represented the regional pedo-climatic conditions; structural, corresponding to the agricultural systems and management practices adopted; institutional, by involving the governmental actions affecting price, credit, commercialization and incentives, and; research and development, relative to the ability to yield increase and to solve problems that restricts the agricultural related activities. Based on these aspects of agricultural systems performance, a hypothesis that can be postulated is that the crop efficiency evaluated in a regional scale could be a pointer of farming development level and this spatial representation could facilitate the identification of the main factors that affect the agricultural production and the viability of the regional agribusiness.

To evaluate the effectiveness of this tool, it was applied the concept of agricultural efficiency to study the sugarcane performance in the State of São Paulo, Brazil. The importance of sugarcane crop has been grown in last years in the context of the global warming due to human activities, as good option of renewable and clean energy. The State of São Paulo is the main Brazilian sugarcane producer, representing more than 60% of production of Brazil. The objective of this paper was to associate techniques of modeling in systems of geographic information for the attainment of maps of maximum and real productivity of sugarcane-of-sugar in the State of São Paulo and, from them, to generate maps of efficiency of the production in three different dates, analyzing the influence of climate and soil in the spatial variability of efficiency in two harvests with different socioeconomic conjuncture.

MATERIAL AND METHODS: Brazilian Institute of Geography and Statistics (IBGE) was the source of sugarcane production data of each county of State of São Paulo in the harvests 1995/1996 and 2002/2003. These harvests were select ~~here~~ because it represents two different social and economic conjunctures of the sugarcane agribusiness in Brazil. Counties production data were converted to observed yield (YO) by dividing it by county harvest area in each year.

To assess the potential (YP) – maximum yield without any restriction element - and real yield (YR) – estimated yield considering the effect of water deficits on crop yield - of sugarcane in the State, one used the agroecological zones method (Doorembos & Kassan, 1979) because it needs few input data and was developed to studies in spatial macro scale, as required by the agriculture efficiency approach applied here. The meteorological data used to simulate YP and YR were supplied by Brazilian Agrometeorological Monitoring System (AGRITEMPO, 2007) in a ten days time step and were processed using a simple computer algorithm. Each time series starts in the beginning of September and finishing at the end of August of next year. For harvest 95/96 the meteorological station network had 62 data points and for harvest 02/03 the meteorological network was constituted by 103 data points. The crop coefficients were obtained in Doorembos & Kassan (1979) by assuming a cycle length of 12 months a sugarcane performance similar to a field in its second cultivation year, with some adjustments provided by Barbieri (1993) and Alvarez et al. (2000).

YO raster maps, with 90m resolution, were generated by the conversion of county vector data. YP and YR maps were generated by the interpolation of sugarcane modeled data using a 90m resolution digital elevation model from SRTM (Zyl, 2001) to correct the interpolation. This procedure was possible because YR data shows a strong relationship with geographical coordinates (latitude and longitude) plus altitude ($R^2$=0.78, 1% of significance).

The spatial representation of sugarcane efficiency was obtained with Spatial Analyst map algebra module of ArcView 9.2 Package, by the ratio between YO and YR images. The area determination of each efficiency range was also made with this software.

To check the influence of abiotic factors on sugarcane crop efficiency it was applied two different statistical tests. For soil, Spearman rank correlation coefficient (Snedecor & Cochran, 1982) was utilized to compare values of efficiency for counties where meteorological stations were installed with soil agricultural aptitude for sugarcane (Ramalho Filho & Beek, 1995). The non-parametric Spearman test was select because soil aptitude is a discrete value, ranging from 1 to 5, in accord to soil quality degree available to sugarcane production, considering the environmental and economically sustainability.

To stablish the relationship between climate and efficiency it was not possible to apply a simple statistical correlation test comparing climate conditions and efficiency values. Since YP and YR was assessed agrometeorological models based on climatic data, a strong auto-correlation would occur in this case, invalidating the posterior inferences. Thus, to analyze the role of climate of sugarcane efficiency, the Pearson coefficient was applied in attempt to found how much does efficiency change for a given change in climate conditions, when it is being represented by YP (Snedecor & Cochran, 1982). Here it is important to remember that YR depends on only climate conditions and YO is a entirely independent variable. Remembering that crop efficiency is the ratio between YO and YR, the correlation level between them seems to be a good approximation of the dependence degree between efficiency in relation to climate conditions.

**RESULTS AND DISCUSSION:** Figure 1a shows that YP in State of São Paulo ranged between 29 to 202 ton $ha^{-1}$ and this range can be considered coherent with maximum yield limits of sugarcane observed in experimental conditions, when all deflationary factors are totally controlled (Hubert, 1968; Muchow et al., 1994; Maule et al., 2001). Minimum YP values seems to be inconsistent with observed yield in the coldest regions of São Paulo, but as these values were found in very few pixels, one did not change it. Including the effect of water deficits on crop yield, it was observed an expressive yield loss in relation to YP, agreeing with values normally observed in field conditions in the State of São Paulo (Figura 1b e 1c), emphasizing the importance of water to sugarcane production. YR values ranged from 26 to 143 ton $ha^{-1}$ in 95/96 and from 24 to 139 ton $ha^{-1}$ in 02/03.

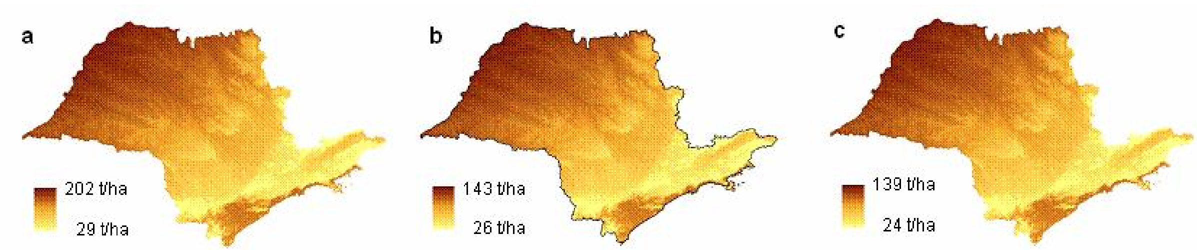


Figure 1. Maps of potential yield to harvest 95/96 (a) and real yield for São Paulo State for harvests 95/96 (b) and 02/03 (c).

Throughout the period analyzed between two harvests it was observed an increment of YO in about 3%, an increase in the cropped area of 17 % and the rise of 7% in the number of counties with economic sugarcane production (data not showed). Figure 2 shows a migration trend of sugarcane to the west region, where it had replaced land originally occupied with low yield pastures (Torquato, 2006) mainly because relatively low prices of these farms in comparison with central and north regions of São Paulo State. The little rise of mean sugarcane yield in São Paulo can be partially attributed to the migration trend, since the economically production level in west seems to be below than the common yield range observed in traditional sugarcane plantations of São Paulo, such as Ribeirão Preto and Piracicaba. In these regions, sugarcane plantations had been at high quality agricultural soils, where plants can reach high growth rates and high yields. Koffler & Donzeli (1987) claim that the spite of the sugarcane seems to be tolerant to ground less fertile, to attain high levels of productivity adjusted ground more under the physical and chemical aspect is essential.

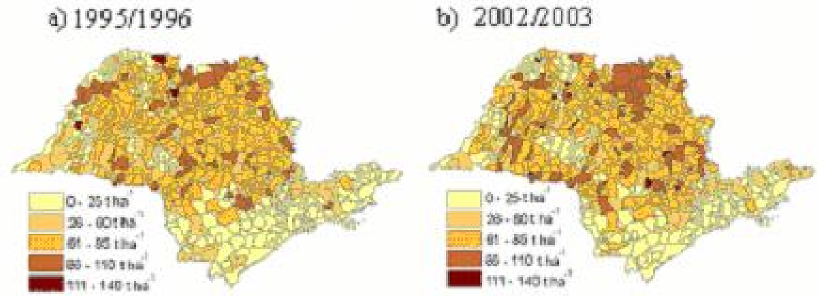


Figure 2. Spatial distribution of sugarcane production in the State of São Paulo at two different dates.

The maps of sugarcane efficiency production (Figure 3) indicate a rise in efficiency levels throughout the period, especially in central and north regions, where the crop yield shows a great increase. When the comparison between efficiency and soil aptitude variability was made, it was identified a high degree of dependence between both, as Spearman test had indicated. For 02/03 harvest, Spearman coefficient was 0.36, allow to conclude that 36% of crop efficiency was due to soil quality (Table 1). For 95/96 harvest, Spearman analysis explains 44% of efficiency variation derived from soil characteristics. The difference between two Spearman coefficients leads to infer about the sugarcane plantations can respond more expressively to soil quality when other factor acting on vegetative development and yield formation phases are controlled. About climate, it is easy to establish an inverse relation with soil relative importance, since when soil takes more importance it becomes the major restrictive element of the system. When soil receives recommended amounts of fertilizers, its restrictive aspects lost importance and climate conditions get more importance.

Table 1. Spearman (soil variability) and Pearson (climate variability) coefficients, and number of point used in evaluated soil and climate influences on crop efficiency in two sugarcane harvest.

| Harvest | n$^o$. points | Spearman Coefficient | Pearson Coefficient |
|---|---|---|---|
| 95/96 | 62 | 0.435 | 0.07 |
| 02/03 | 103 | 0.357 | 0.13 |

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