SOYBEAN YIELD ESTIMATION BY AN AGROMETEOROLOGICAL MODEL IN A GIS

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ABSTRACT: Agrometeorological models interfaced with the Geographic Information System – GIS are an alternative to simulate and quantify the effect of weather spatial and temporal variability on crop yield. The objective of this work was to adapt and interface an agrometeorological model with a GIS to estimate soybean [G*lycine max* (L.) Merr.] yield. Yield estimates were generated for 144 municipalities in the State of Paraná, Brazil, responsible for 90% of the soybean production in the State, from 1996/1997 to 2000/2001. The model uses agronomical parameters and meteorological data to calculate maximum yield which will be penalized under drought stress. Comparative analyses between the yield estimated by the model and that reported by the Paraná State Department of Agriculture (SEAB) were performed using the "*t*" test for paired observations. For the 1996/1997 year the model overestimated yield by 10.8%, which may be attributed to the occurrence of fungal diseases not considered by the model. For 1997/1998, 1998/1999 and 1999/2000 no differences ($P > 0.05$) were found between the yield estimated by the model and SEAB's data. For 2000/2001 the model underestimated yield by 10.5% and the cause for this difference needs further investigation. The model interfaced with a GIS is an useful tool to monitor soybean crop during growing season to estimate crop yield.
Key words: geographic information system, municipalities, weather, crop

PRODUTIVIDADE DE SOJA ESTIMADA POR MODELO AGROMETEOROLÓGICO NUM SIG

RESUMO: Os modelos agrometeorológicos integrados em Sistemas de Informação Geográfica - SIG são uma alternativa para simular e quantificar o efeito da variabilidade espacial e temporal do clima sobre a produtividade agrícola. O objetivo deste trabalho foi adaptar e integrar um modelo agrometeorológico num SIG para estimar a produtividade da soja [*Glycine max* (L.) Merr.]. Foram geradas estimativas de produtividade para 144 municípios do Estado do Paraná, responsáveis por 90% da produção de soja no Estado, em cinco anos-safra no período de 1996/1997 a 2000/2001. O modelo utiliza parâmetros agronômicos e dados meteorológicos para o cálculo da produtividade máxima, a qual é penalizada quando ocorre estresse hídrico. A análise da comparação entre as estimativas municipais obtidas pelo modelo e aquelas divulgadas pela Secretaria de Estado da Agricultura e do Abastecimento (SEAB) do Paraná foi feita através do teste "t" para pares de observação. No ano safra 1996/1997 o modelo superestimou a produtividade em 10,8% em relação à SEAB, o que pode ser atribuído à ocorrência de oídio, cujo efeito não é considerado no modelo. Nos anos safras de 1997/1998, 1998/1999 e 1999/2000 não foram identificadas diferenças ($P > 0,05$) entre as estimativas do modelo e da SEAB. Em 2000/2001 a produtividade foi subestimada pelo modelo em 10,5%, sendo que as causas desta diferença precisam ser melhor investigadas. O modelo integrado no SIG mostrou ser uma ferramenta viável para acompanhar a cultura da soja ao longo da estação de crescimento, e estimar a produtividade em municípios do Estado do Paraná.
Palavras-chave: sistema de informação geográfica, municípios, clima, safra

INTRODUCTION

Yield estimation of soybean [*Glycine max* (L.) Merr.] in Brazil is accomplished subjectively through inquires to farmers, analysis of previous crop yield data and observation of meteorological conditions during the growing season. Based on this information, key people the soybean sector try to achieve consensual estimates on both, planted area and expected crop yield. The subjectivity of this procedure opens up opportunities to look for alternatives on more objective methods which can provide reliable information on crop yield.

The soybean business in Brazil has benefited from continuous technological improvements, responsible for the significant increase in soybean production, through increasing productivity rather than cultivated area. Therefore,

variation on soybean production is largely related to the observed climatic conditions during each year. The effect of weather on crop yield can be estimated using mathematical models, as demonstrated by Baier (1973), Doorenbos & Kassam (1979), Pedro Jr. et al. (1984), Rudorff (1985), Berlato (1987), Rudorff & Batista (1990, 1991), Fontana & Berlato (1998), Moraes et al. (1999), Hoogenboom (2000), Fontana et al. (2001), among others.

For non-irrigated crops such as soybean, both amount and distribution of rainfall during the growing season are important yield determinants. Doorenbos & Kassam (1979) proposed a model to quantify water stress effect on the final yield of several agricultural crops based on the relationship between actual and maximum evapotranspiration, i.e. whenever the amount of water on demand is larger than that which is available, potential yield will be penalized.

Recent advances in the development of Geographical Information Systems (GIS) have facilitated spatial data analysis for large geographical areas. Crop yield models can also benefit from the GIS technology to analyze and model agrometeorological data (Hartkamp et al., 1999; Dang et al., 2000; Sugawara, 2001).

The objective of this work was to integrate an agrometeorological model in a Geographical Information System to quantify the effect of agrometeorological variables on soybean yield in municipalities of the State of Paraná.

MATERIAL AND METHODS

Crop monitoring and yield estimation were accomplished by using an agrometeorological model integrated to a GIS (AGROMET; Sugawara, 2001) for 144 municipalities in the State of Paraná, Brazil (Figure 1), which are responsible for about 90% of the soybean production in the State. The study was conducted over five growing seasons from 1996/1997 to 2000/2001. Yield outputs from the
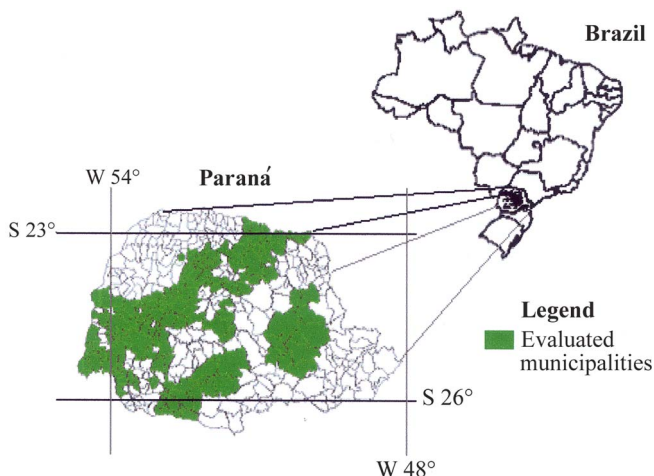
AGROMET were compared to the reported yield estimates of the Paraná State Department of Agriculture (SEAB), which were used to adjust and validate the model outcome.

The agrometeorological model integrated to the GIS is based on Doorenbos & Kassam (1979). Rudorff & Batista (1990) employed the method described by the former authors and developed a model in FORTRAN language to generate sugarcane yield estimates for a small region with weather data coming from a single weather station. In the present study this model was adapted for soybean crop and integrated to a GIS with a database management system interface using the SPRING (Georeferenced Information Processing System) software package version 3.6 (Câmara et al., 1996; SPRING, 2002). The LEGAL (Language for Algebraic Geoprocessing) programming module, within the SPRING software, was used to implement the several model procedures, which are reported in Sugawara (2001).

Weather data were obtained from 32 stations of the State of Paraná. The model used the following variables: solar radiation, rainfall, air temperature, relative air humidity and wind speed. These data were then averaged on a biweekly basis, except for rainfall, which was summed up biweekly. A regular grid with 8000 m resolution in X and Y was generated using the quadrant weight average technique for interpolation (Felgueiras, 2001) to obtain the meteorological data for each municipality (Figure 2).
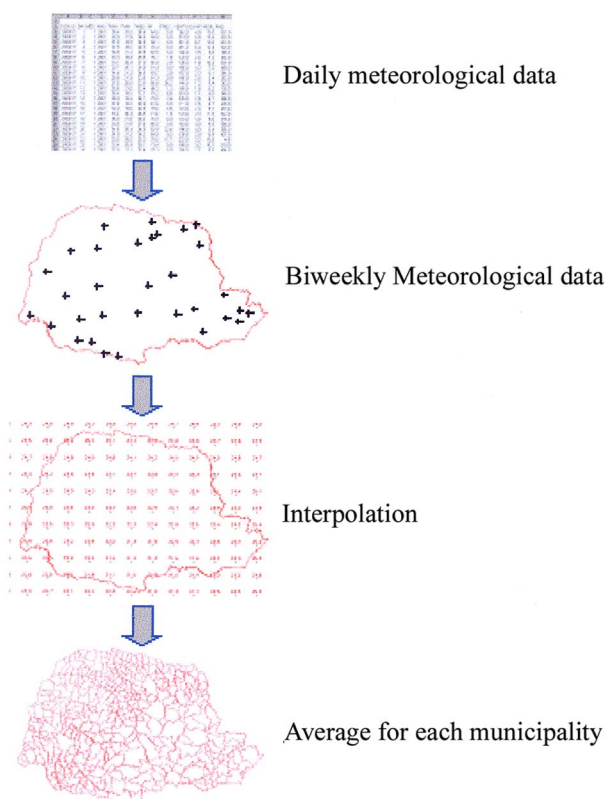

Figure 1 - Paraná State and the evaluated municipalities within the soybean production area (SEAB, 1987).

Figura 2 - Steps performed to obtain the biweekly meteorological data for each municipality using the SPRING software.

Municipality boundaries for the State of Paraná are available in the SPRING software. Soil water holding capacities were obtained from a digital soil map. A global remote sensing image of the state, acquired on April 09, 2000 by the WFI (Wide Field Imager) sensor on board of the CBERS (China-Brazil Earth Resources Satellite) satellite, was used to associate the spatial variability of the meteorological data to the areas mainly designated for soybean production within each municipality. This image was acquired shortly after soybean harvest and areas of intense agricultural activity appear well enhanced on the image. Yield estimates by the model (AGROMET) were based on the following equation (Doorenbos & Kassam, 1979):

$$Y_e = Y_m \left[1 - k_y \left(1 - \frac{\text{ET}_a}{\text{ET}_m} \right) \right] \qquad (1)$$

where Y_e is the estimated yield (kg ha^{-1}), Y_m the maximum yield (kg ha^{-1}), k_y the yield response factor, ET$_a$ the actual evapotranspiration (mm) and ET$_m$ the maximum evapotranspiration (mm).

Maximum yield (Y_m) is established by the genetic characteristics of the crop and by the degree of crop adaptation to the environment (Doorenbos & Kassam, 1979). In this work, Y_m was adjusted to the maximum yield average achieved for a healthy crop without water and nutrient deficiencies. Y_m (kg ha^{-1}) was estimated by the following restrictions and equations:

If $y_m > 20$ kg ha^{-1} h^{-1}, then:

$$Y_m = c_L.c_N.c_H.G.(F(0.8 + 0.01y_m)y_o + (1-F)(0.5 + 0.025y_m)y_c), \quad (2)$$

If $y_m < 20$ kg ha^{-1} h^{-1}, then:

$$Y_m = c_L.c_N.c_H.G.(F(0.5 + 0.025y_m)y_o + (1-F)(0.5y_m)y_c), \qquad (3)$$

where c_L is the leaf area correction factor; c_N is the net dry matter production factor; c_H is the harvest factor; G is the total growing period (days); F is the fraction of the day which is cloudy; y_m is the production rate of dry matter for the soybean crop (kg ha^{-1} h^{-1}); y_o is the production rate of dry matter of a standard crop in completely cloudy days (kg ha^{-1} day^{-1}); y_c is the production rate of a standard crop in clear days (kg ha^{-1} day^{-1}). The leaf area correction factor (c_L), which is related to the leaf area index (LAI), is determined by the following equation:

$$c_L = 0.515 - e^{(-0.664-(0.515*LAI)}, \qquad (4)$$

where LAI was obtained from Fontana et al. (1992), for non-irrigated conditions. The net dry matter production factor (c_N) compensates the energy used in respiration, which is a function of temperature. When the mean temperature is below 20ºC, the soybean plant uses 40% of the absorbed energy for maintenance and when the mean temperature is above 20ºC, it uses 50%. The harvest factor (c_H) indicates the relationship between dry matter production and grain production and was assumed to be 0.32.

The maximum evapotranspiration (ET$_m$) was calculated using potential evapotranspiration (ET$_o$):

$$\text{ET}_m = k_c.\text{ET}_o, \qquad (5)$$

where k_c is the crop coefficient and ET$_o$ is computed using the Penman method (Frère & Popov, 1980).

The determination of the actual evapotranspiration (ET$_a$) depends on three factors: the maximum evapotranspiration (ET$_m$), the remaining available soil water and the available soil water index (*ASI*; Doorenbos & Kassam, 1979). The water balance, which impacts the calculation of *ASI*, was obtained using the method proposed by Thornthwaith & Mather following the description presented by Mota (1979) and adapted by Rudorff (1985). ET$_a$ was determined based on a look-up table given by Doorenbos & Kassam (1979) that considers the three factors just mentioned. Finally all necessary variables to estimate crop yield (Y_e) based on Equation 1 were obtained. The statistical comparison between the soybean yield of the AGROMET and that reported by the SEAB, for each municipality, was performed using the "*t*" test (Steel & Torrie, 1980).

The soybean yield monitoring over the growing season, on a biweekly basis, was accomplished by using a penalizing index (k_p) according to:

$$k_p = 1 - k_y \left(1 - \frac{\text{ET}_a}{\text{ET}_m} \right) \qquad (6)$$

Y_m and k_p were partially evaluated for nine biweekly periods considering a growing season of 135 days beginning on November 1st and ending on March 15.

RESULTS AND DISCUSSION

Only the mean yield estimate for the State for each growing season is presented. For the 1996/1997 growing season the model overestimated soybean yield by 10.8% in relation to SEAB (Table 1), which corresponds to a significant difference of 284 kg ha^{-1} (t=15.71; $\alpha < 0.05$). This difference can be attributed to the occurrence of a fungal disease (SEAB, 1997) in susceptible soybean cultivars as weather conditions were favorable for its development (Yorinori, 2000). The disease effect on soybean yield was not considered in the model; however, this effect can be modeled through other methods in order to correct the AGROMET estimation.

For the 1997/1998, 1998/1999 and 1999/2000 seasons no differences were found between the AGROMET and the SEAB soybean yield estimates (Table 1) indicating that the climatic effect on soybean yield was well modeled by the AGROMET. For the 2000/

Table 1 - Mean and standard deviation of soybean yield in municipalities of the State of Paraná based on estimates from SEAB and AGROMET model, t test values for paired observations, absolute difference and relative difference among estimates.

Crop year		Mean Yield	Standard Deviation	t value	Difference	Relative Difference
		kg ha^{-1}			kg ha^{-1}	%
1996/1997	SEAB	2626	226.8	15.7*	284	10.8
	AGROMET	2910	75.9			
1997/1998	SEAB	2573	320.9	1.3^{ns}	34	1.3
	AGROMET	2607	96.3			
1998/1999	SEAB	2785	278.9	0.7^{ns}	17	0.6
	AGROMET	2802	73.3			
1999/2000	SEAB	2518	381.1	0.3^{ns}	8	0.3
	AGROMET	2526	175.6			
2000/2001	SEAB	3070	260.0	-14.7*	-323	-10.5
	AGROMET	2747	144.9			

^{ns}, not different at 5% for t test; *different at 5% for t test.

2001 season the AGROMET underestimated soybean yield by 10.5%, as compared to the SEAB estimate, which corresponds to a difference of 323 kg ha^{-1} (t=-14.71; α < 0.05). The reasons for this underestimation may be partly related to parameters that still need to be adjusted and refined in the model such as different sowing dates and soybean cultivars. Also, a greater number of weather stations throughout the State of Paraná will likely improve the spatial distribution of the weather variables, especially rainfall, which is the most important and also the most variable. After the adjustment of the AGROMET parameters they were kept the same for the five growing seasons and, therefore, the variation in estimated soybean yield across years is only due to the variation of the weather data.

The relative difference between yield estimation of AGROMET and SEAB, for the five growing seasons was not consistent (Figure 3). Therefore, it was not possible to account for possible technological differences among municipalities.

The penalizing index (k_p) for biweekly periods throughout the growing season in each of the five analyzed cropping years (Figures 4 through 8), indicate the occurrence of water deficit periods and their impact on yield. In 1996/1997 (Figure 4) the water deficit occurred only during the first half of January, when the value of k_p, for the majority of the municipalities, varied between 0.65 and 0.80. This indicates that the dry matter accumulation for soybean was reduced by 20 to 35%. For 1997/1998 (Figure 5) yield was impacted by "El Niño", which usually favors yield (SEAB, 1998). However, relative short dry periods affected the availability of water for the crop during December and January, reducing yield in several regions of the State. In 1998/1999 (Figure 6) a mild water deficit was observed early in the growing season resulting in a heterogeneous development of several soybean fields

(SEAB, 1999). A more severe water deficit was recorded for the months of December and January when the potential crop yield was heavily penalized. In 1999/2000, low rainfall in November, December and January caused a decrease in soybean yield in almost all municipalities (Figure 7). According to SEAB (2000) the loss was not greater due to the high technological level of the farmers.

Finally, in 2000/2001 (Figure 8) soybean potential yield was penalized in the second half of December and in January for most of the municipalities. The 2000/2001 season was similar in weather conditions to 1998/1999 and, consequently the AGROMET output was also very similar for these two season. It is possible, however, that the water deficit observed in 2000/2001 was less critical than in 1998/1999 due to differences in planting dates.

The SPRING software, with its LEGAL programming module, was found to be adequate to integrate the agrometeorological model and the weather database in the GIS. The AGROMET is a powerful tool to monitor the weather impact on soybean yield on an operational basis, at a relatively low cost and reduced time, for both local (municipalities) and regional (State) estimates.

CONCLUSION

The agrometeorological model integrated in a GIS (AGROMET) proved to be a powerful tool to analyze the effect of both temporal and spatial variability of weather data on soybean yield. AGROMET generated objective soybean yield estimates comparable to the official reported estimates for three out of the five growing seasons analyzed. AGROMET also demonstrated to be an important tool to monitor soybean crop throughout the growing season and generate objective yield estimation at both municipality and state levels.
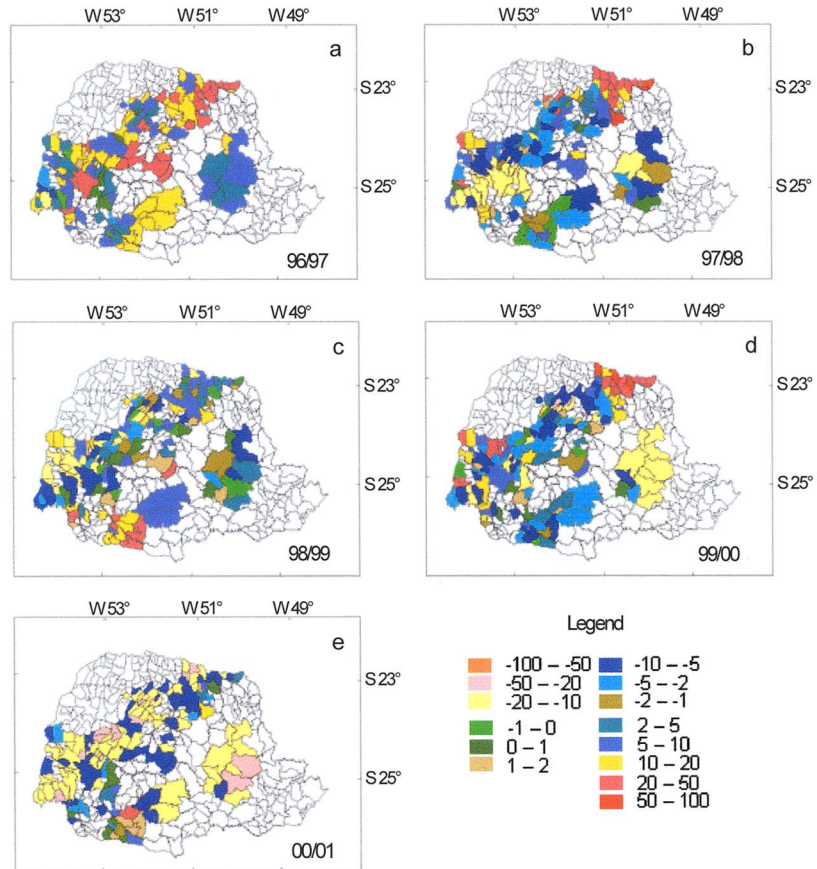
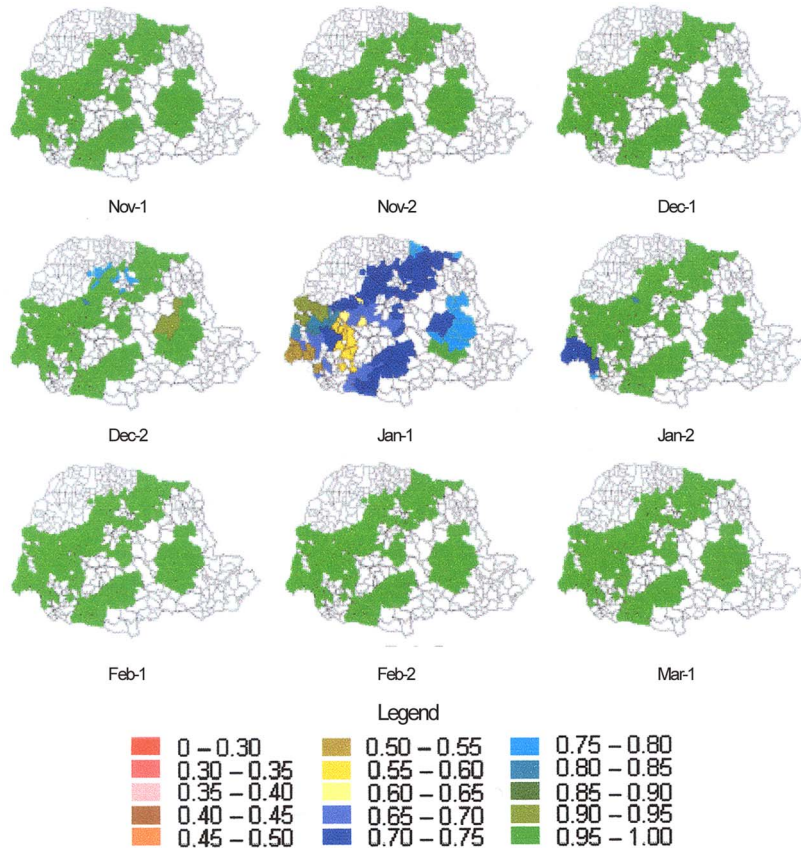Figure 3 - Relative difference (%) between yield estimation of AGROMET and SEAB.

Figure 4 - Biweekly penalizing index of soybean yield in Paraná State – crop year 1996/1997.
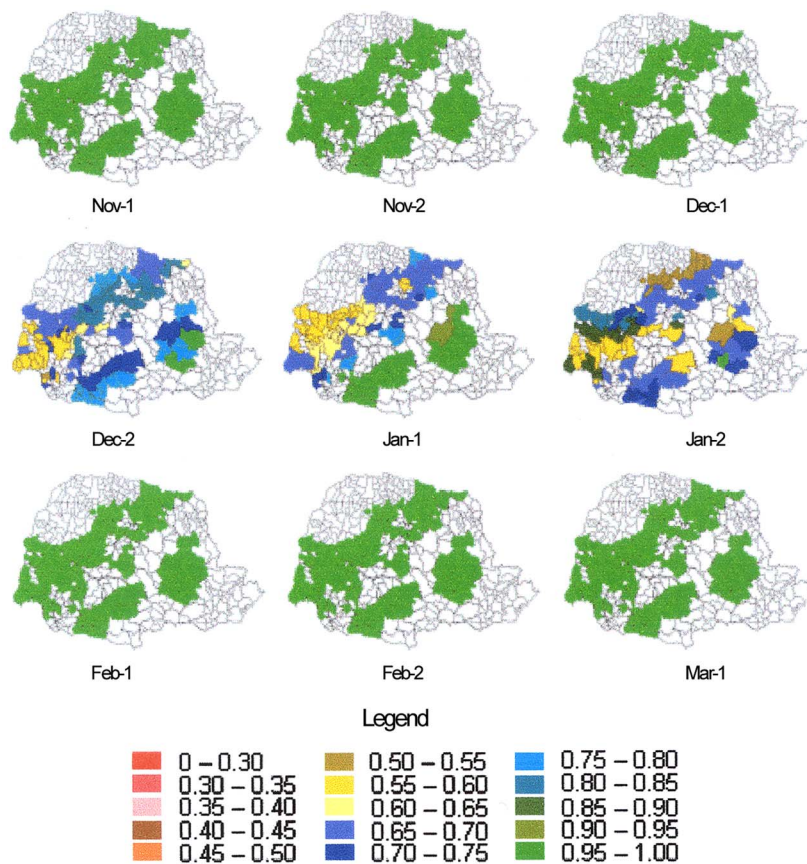
Figura 5 - Biweekly penalizing index of soybean in Paraná State – crop year 1997/1998.
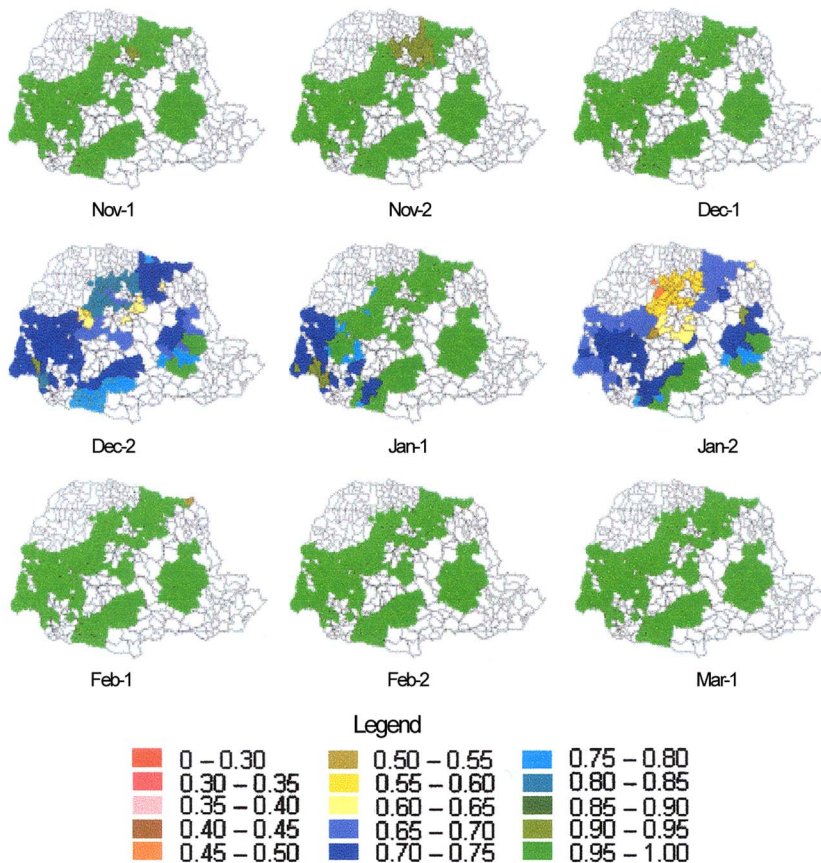

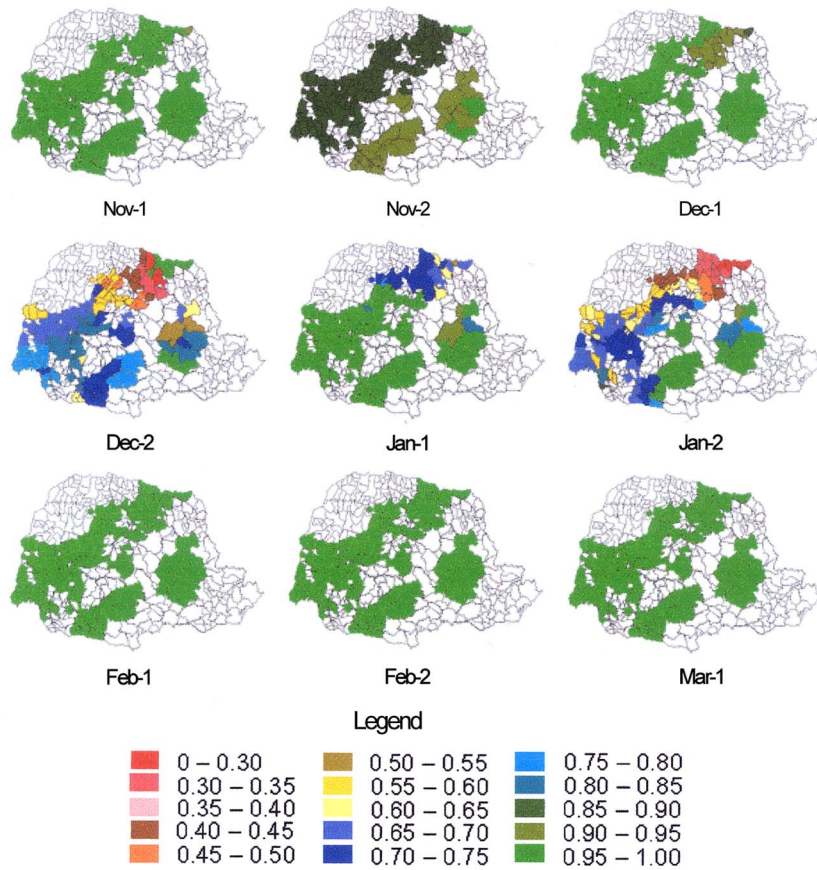Figura 6 - Biweekly penalizing index of soybean in Paraná State – crop year 1998/1999.

Figure 7 - Biweekly penalizing index of soybean in Paraná State – crop year 1999/2000.
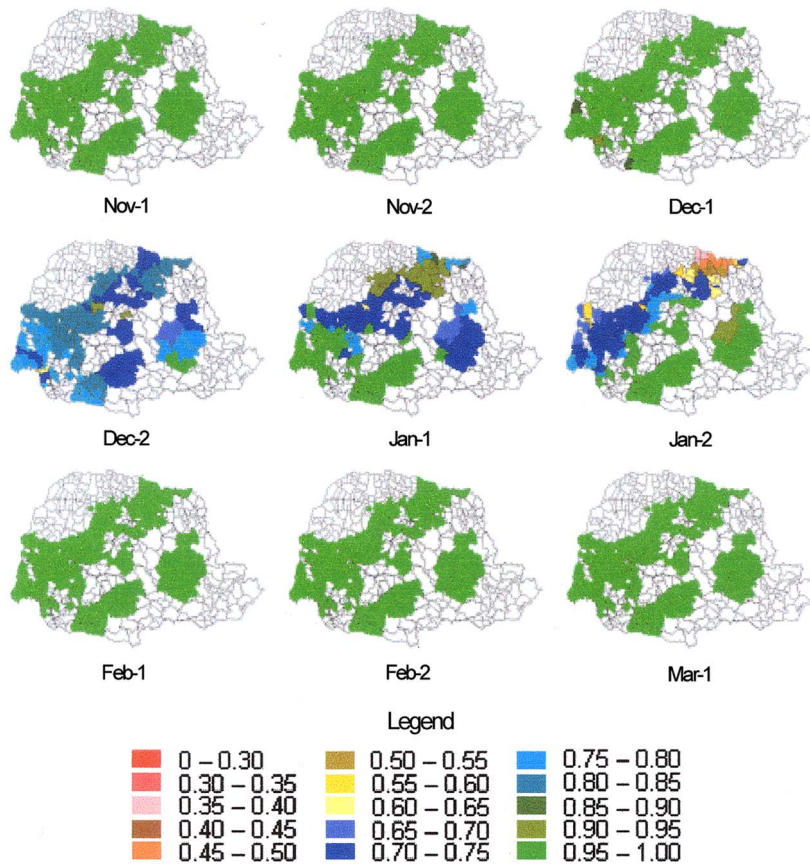

Figure 8 - Biweekly penalizing index of soybean in Paraná State – crop year 2000/2001.

ACKNOWLEDGEMENTS

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