http://dx.doi.org/10.1590/1678-4499.0439

Using temporal NDVI/MODIS profiles for inferences on the crop soybean calendar

Denise Cybis Fontana ([1*]); Daniele Gutterres Pinto ([1]); Amanda Heemann Junges ([2]); Carolina Bremm ([2])

([1]) *Universidade Federal do Rio Grande do Sul (UFRGS), Faculdade de Agronomia, Departamento de Plantas Forrageiras e Agrometeorologia, Avenida Bento Gonçalves, 7712, 91540220 Porto Alegre (RS), Brazil.*

([2]) *Fundação Estadual de Pesquisa Agropecuária (FEPAGRO), Rua Gonçalves Dias, 570, 90130-060 Porto Alegre (RS), Brazil.*

(*) Corresponding author: dfontana@ufrgs.br

***Received:** Dec. 10, 2014; **Accepted:** Mar. 16, 2015*

Agrometeorology /Article

Abstract

A major challenge for grain yield modeling in the context of estimates made operationally for large areas is related to the identification of periods in which annual crops show greater susceptibility to environmental stress. For soybean grown in the spring-summer period in southern Brazil, the main risk factor is the occurrence of water stress during flowering and grain filling. These subperiods occur at different times across the production region due to differences in management practices of each farmer. This study aimed to relate the soybean crop calendar to the temporal profiles of normalized difference vegetation index (NDVI/MODIS), in order to present/validate a low cost technology with adequate accuracy for crop monitoring and harvest prediction. Thus, we analyzed data from soybean crop calendar (subperiods of flowering, grain filling and maturation) from EMATER (RS) regions and NDVI MODIS images. The NDVI temporal profiles allow monitoring the development of the soybean crop biomass and determining the occurrence of subperiods. Differences in NDVI values between harvests, regions and subperiods demonstrate the sensitivity of this index in detecting the responses of soybean plants to environmental conditions. Because NDVI data are generated from MODIS images, it is possible to create maps with information about the subperiods for all harvests and throughout the State, which enables greater temporal and spatial details compared to data currently available.

Key words: cycle sub-periods, mapping, flowering, grain filling and maturation.

1. INTRODUCTION

Information on the location in time of the main subperiods of the crop cycle is an important tool in many activities. In the agronomic context, this information is useful in studies characterizing the climate-plant relationship, as annual crops have different periods of susceptibility to environmental stress (Monteiro, 2009). The location in space and time of the occurrence of periods of increased susceptibility (also called critical) is a major challenge for grain yield modeling in order to generate operationally estimates of crop for large areas.

Crop calendars correspond to tables containing the information of the planted area percentage found at certain subperiod of the cycle (vegetative growth, flowering, grain filling and maturation) and are usually elaborated by public institutions of rural extension. In the Rio Grande do Sul State, EMATER (RS) (Associação Rio-grandense de Empreendimentos de Assistência Técnica de Extensão Rural) provides fortnightly information about the main crops, representing a source of data almost exclusive for the monitoring of crops in real time, especially regarding the development of a particular crop in a given region. However, gathering this information requires time and is associated with a high cost for its implementation in the various producing regions. In the State, the crop calendar is available for the 10 regions of EMATER (RS), but without spatial detail of the data in the municipalities composing each region, or even within municipalities.

In this context, satellite imagery, especially of high temporal resolution sensors, such as MODIS (Moderate Resolution Imaging Spectroradiometer) aboard the TERRA satellite, can generate information on agricultural crops, providing data with frequency compatible with phenological stages and with adequate spatial representation within the producing regions (Rudorff et al., 2007).

From images collected by MODIS, several products are designed, which are available for a relatively long period, from 2000, and complement the NDVI data provided by NOAA (Huete et al., 2002). These data sets represent the largest and most complete historical series about the spatial and temporal dynamics of global biomass.

The NDVI is obtained by the ratio between the difference and the sum of the near infrared and red reflectances. Since the NDVI is significantly associated with green plant biomass (Jensen, 2009; Ponzoni & Shimabukuro, 2007), this has been the index most frequently used in studies on the behavior of vegetation. Of note is the use of NDVI from MODIS images in monitoring the development of crops (Jacóbsen et al., 2003; Junges & Fontana, 2009; Wagner et al., 2013), grain modeling (De Melo et al., 2008; Rizzi & Rudorff, 2007; Fontana et al., 2007; Mercante et al., 2010) and acreage estimation (Gusso et al., 2012; Johann et al., 2012; Santos et al., 2014).

The hypothesis raised in this work is that it is possible to use NDVI/MODIS images to infer on the calendar of crops that occupy large areas in the Rio Grande do Sul State. Among these, soybean is the main spring-summer crop in the state, occupying around 4 million hectares in the 2012 harvest. Traditionally, soybean crops are concentrated in the northern Rio Grande do Sul State. Currently, the planted area is advancing to the south of the State due to technologies that enable soybean cultivation in lowland areas, which were previously used only for rice cultivation. In soybean, the main risk factor is the occurrence of water stress during flowering and grain filling. In this way, strategic methods try to identify these subperiods, which occur at different times across the production region due to differences in management practices of each farmer.

This study aimed to relate the crop calendar to the temporal profiles of NDVI/MODIS for soybean crop in the Rio Grande do Sul State in order to present/validate a low cost technology with adequate accuracy for crop monitoring.

2. MATERIAL AND METHODS

This study analyzed data of the soybean crop calendar of nine out of 10 regions of EMATE (RS), in the Rio Grande do Sul State: Bagé, Caxias, Erechim, Estrela, Pelotas, Ijuí, Passo Fundo, Santa Maria and Santa Rosa (Figure 1).

Each region was characterized as the temporal evolution of the soybean crop calendar and temporal profiles of NDVI/MODIS, in the crop years from 2000/2001 to 2009/2010, totaling ten years.

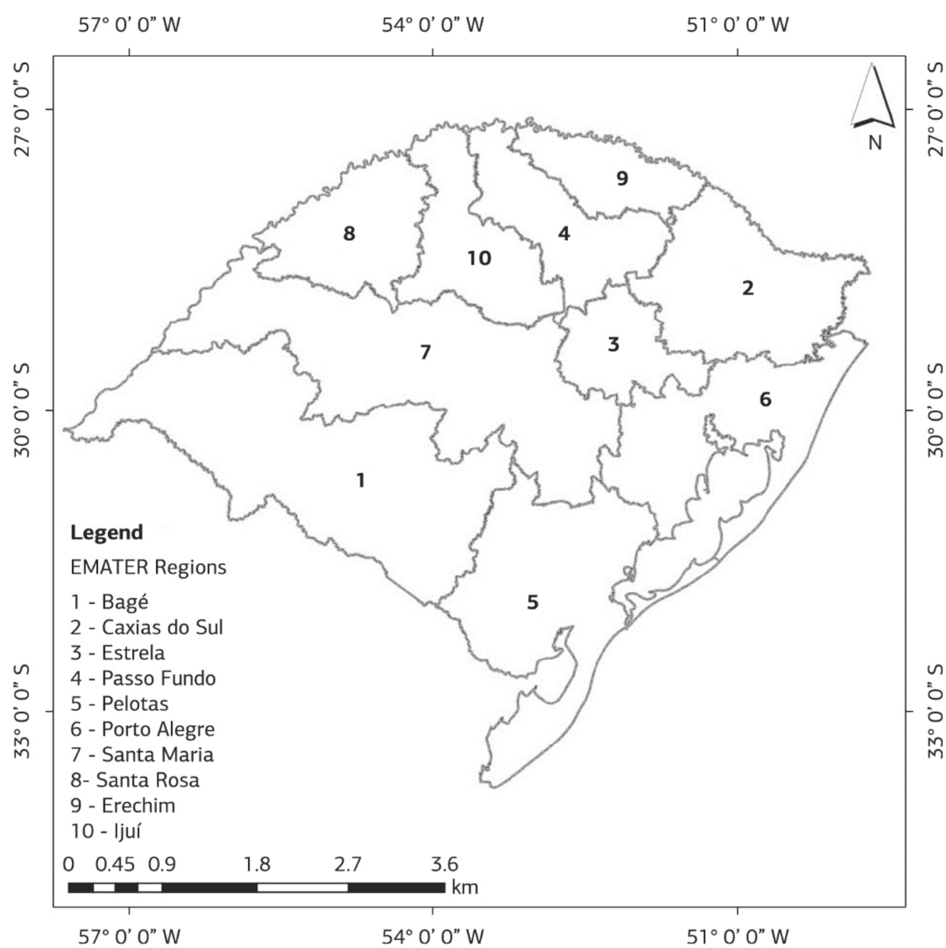

Figure 1. Rio Grande do Sul State and EMATER (RS) Regions.

Data of crop calendar data for the study period, routinely published in the bulletin of the institution (EMATER, 2008), were provided by EMATER (RS). In this work, we analyzed the following subperiods of the soybean crop cycle: flowering, grain filling and maturation. The average crop calendars were obtained by calculating the average percentage of planted area in which the crops were in each of the three subperiods above. To analyze the variability between years and between regions, bar charts were constructed with the start and end dates of the subperiods analyzed, as well as the date at which it was reached the maximum acreage in each subperiod.

To elaborate NDVI temporal profiles for each region and year, we used MODIS images, MOD13Q1 product, collection 005, relating to compositions of maximum value every 16 days, with a spatial resolution of 250 m. The temporal NDVI/MODIS profiles were developed with the images of the fortnights from October to May, coinciding with the planting, growth and development of soybean in the Rio Grande do Sul State (agricultural harvest).

In NDVI/MODIS images, the area planted with soybean was identified by crop masks, which is based on higher temporal variability of soybean biomass over the cycle, compared to other natural targets. For each harvest, the crop masks were obtained from the methodology of classification key (Santos et al., 2014). First, 5 binary images were created (class 1 = soybean; class 0 = no soybean) sequentially over time. The assignment of the value 1 followed the criteria: Sowing: NDVI≤0.5; Growth: DIF ($NDVImax-NDVImin_i$)≥0.35; Maximum development: NDVI≥0.75; Decline: DIF ($NDVImax-NDVImin_f$)≥0.35; Harvest: NDVI≤0.5 (the indices i and f indicate the initial and final portion of the soybean cycle, respectively). Subsequently, these five binary images were superimposed to form a single crop mask, in which the pixels classified in the class soybean were those that, by meeting the criteria set in all steps, received the value 1. The pixels forming the crop mask were used to obtain the average value of NDVI (simple average) and for outlining the evolution of the index along the harvest, thus constituting the temporal profile of NDVI/MODIS.

Data of the soybean crop calendar were related to NDVI/MODIS temporal profiles through the identification of NDVI values that occurred in each subperiod of the soybean crop cycle in all harvests and regions. After, we calculated the mean value and the standard deviation of NDVI for each subperiod. The spatial representation of subperiods of flowering, grain filling and maturation was made using the municipality of Cruz Alta (one of the municipalities with the largest acreage) in the 2008/2009 growing season (high yield). For the construction of these images, we used the values of NDVI including the pixels that had, for each date, values between the mean and ±0.25 standard deviation.

Lastly, data were subjected to analysis of variance (ANOVA), at 5% significance, to check for significant differences in NDVI values between subperiods of the cycle, between regions and between harvests. For the analysis of differences between subperiods and between regions, we included the fixed effects of subperiod and location, and the harvest was considered as a random effect. To test the difference in yield, the effects of harvests and subperiods were considered as fixed, and the regions, as a random effect. When the F test was significant for NDVI ($p<0.05$), means were compared by Tukey's test, in the same level of significance, using the statistical software SAS (2008).

3. RESULTS AND DISCUSSION

In the average of the years analyzed, the soybean crop calendar in the Rio Grande do Sul State prepared by EMATER (RS) (Figure 2) was characterized by the occurrence of flowering, especially in January and February, grain filling, in February and March, and physiological maturity in April. The average crop calendar shows consistency with technical recommendations for soybean crops in the State, both for the type of cycle of the cultivars and the periods indicated for sowing (Brasil, 2013). For most of the municipalities of the Rio Grande do Sul State it is recommended the period starting from October 15 to December 25 for sowing (Cunha et al., 2001). Considering November 20 as central date of the recommended period for soybean sowing in the State, with an average cycle of 140 days (Thomas & Costa, 2010), the completion of the development cycle (physiological maturity) would be on April 20, consistent with the average soybean crop calendar (Figure 2).

The analysis of the variability between crop calendars and regions (Figure 3) identified changes in the fortnight at which each subperiod occurred. However, this variation was relatively low, without temporal displacement exceeding

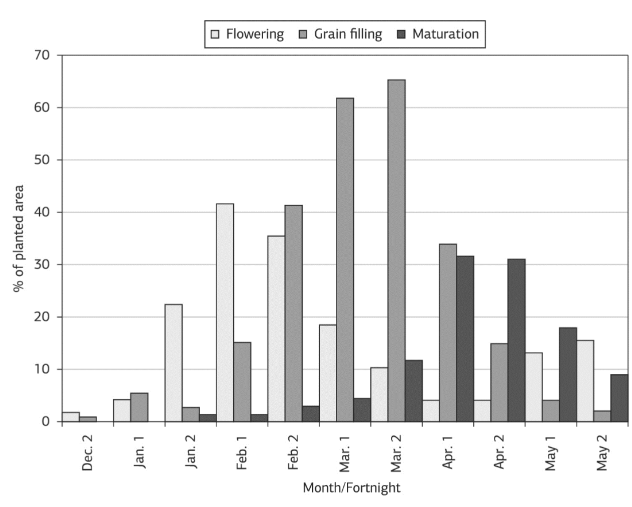

Figure 2. Percentage of area planted with soybean at flowering, grain filling and physiological maturity in the Rio Grande do Sul State. Period from 2000/2001 to 2009/2010. Data source: EMATER (2008).

one fortnight, compared to the average data for the State (Figure 2). In certain years there were greater temporal displacements than the mentioned, which is possibly due to environmental conditions (especially weather), which may have anticipated or delayed crop establishment. Although it has occurred with low frequency in the analyzed data set, in these years the mechanisms detecting the variability of the crop calendar in real time are most needed, so that mitigation measures to adverse events can be adopted.

Importantly, the consistency of the data (Figures 2 and 3) with the reality of soybean production region in the State is because EMATER (RS) systematically perform fortnightly research on the development of major crops, which cover about 70-80% of the planted area. Thus, it is assumed that they can be used as 'reference data', from which, the other data, such as those obtained by remote sensing techniques, can be evaluated and tested for quality and consistency. In the context of this study, the set of data comes from NDVI MODIS images, which are free and available in near real time every 16 days.

The profiles in figure 4 show the evolution of the average NDVI of areas planted with soybean in the various regions. These temporal profiles consist of spectral data that report the time evolution of green biomass in crops, given the high association of this vegetation biophysical parameter with NDVI (Jensen, 2009). The areas planted with soybean in all regions and harvests showed the typical pattern for annual crops, as is the case of soybean (De Melo et al., 2008; Rizzi & Rudorff, 2007). The NDVI values were low at the start of the cycle, associated with crop establishment (lower density of green biomass), increased until the plants reached maximum growth and then decreased according to plant senescence.

The similarity in profiles between regions can be associated with the short period for sowing soybean recommended in the State, which makes the crop cycle similar between

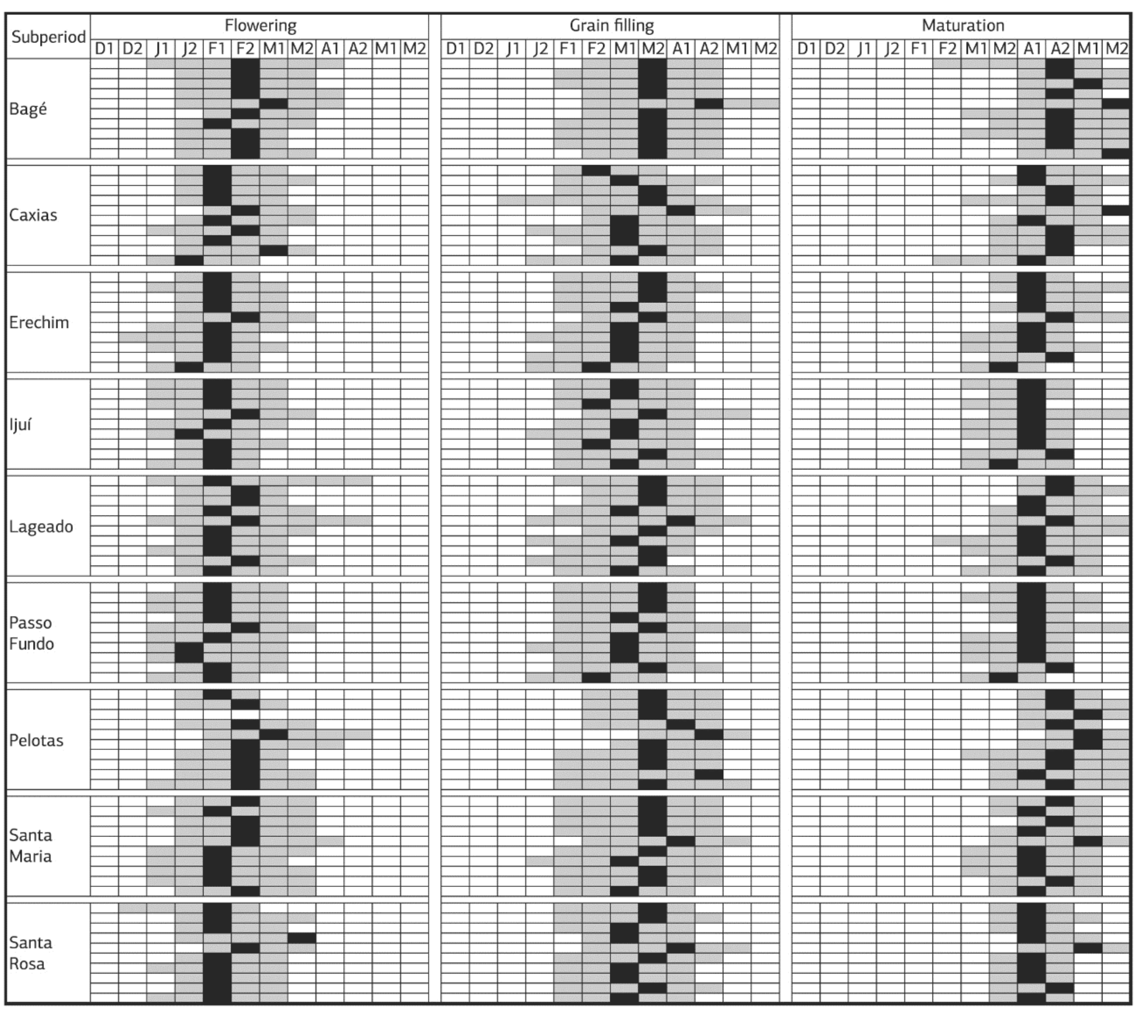

Figure 3. Variability in the soybean crop calendar in the Rio Grande do Sul State for the subperiods of flowering, grain filling and maturation in the first and second half of December (D), January (J), February (F), March (M), April (A) and May (M). Gray bars indicate the start (5%) and final (95%) periods of each subperiod; black bars indicate the fortnight at which it was reached the maximum acreage in the subperiod. The lines in each region are associated with the period from 2000/2001 to 2009/2010. Data source: EMATER (2008).

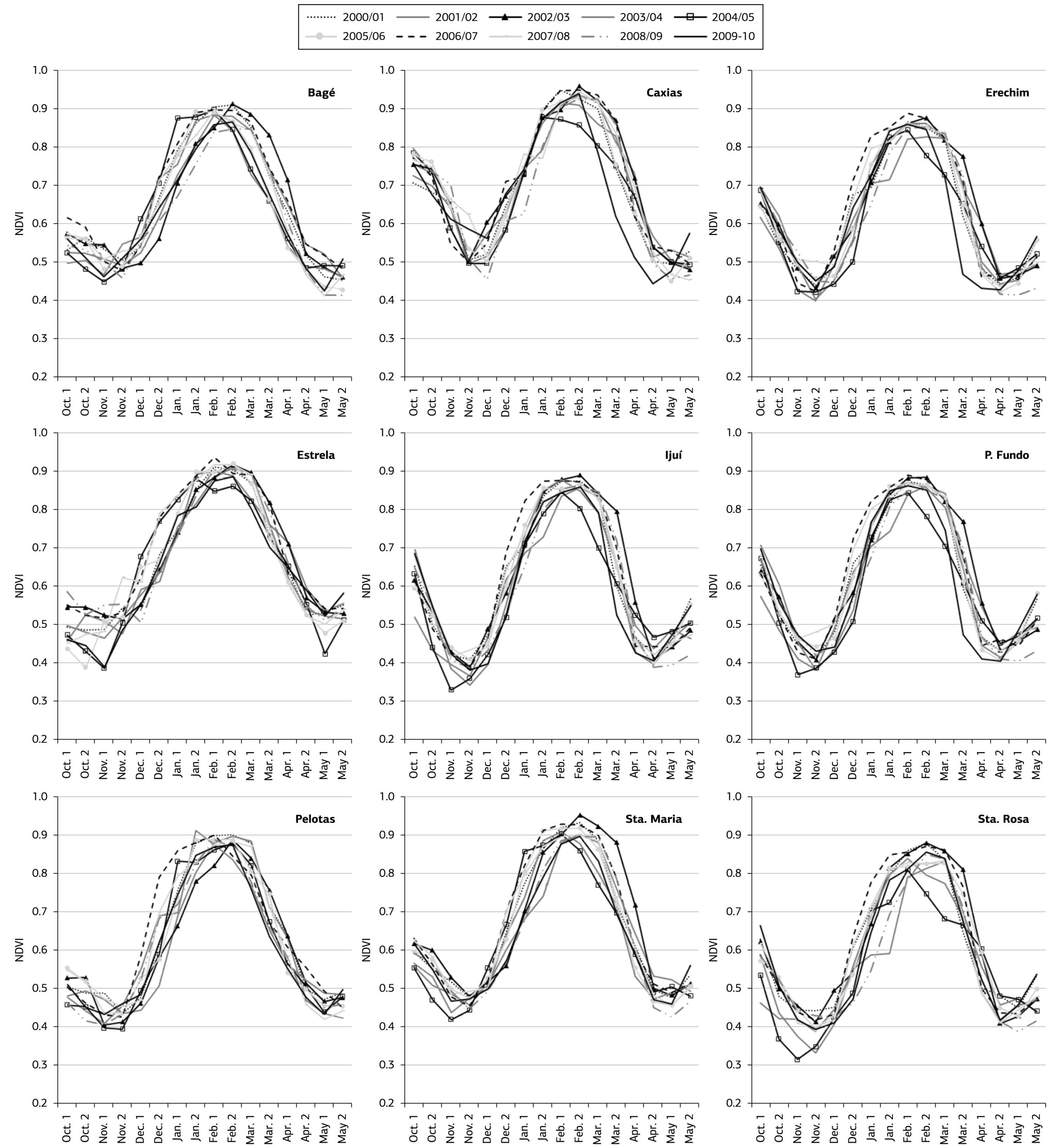

Figure 4. NDVI temporal profiles of areas planted with soybean in nine regions of EMATER (RS) in the period from 2000/2001 to 2009/2010.

regions and between years. Nevertheless, differences in the management and the availability of environmental resources (especially weather variables) between regions defined significant differences in the mean values of NDVI (Table 1).

The regions presenting the highest mean values of NDVI are those that, according to official data of the period (IBGE, 2013), also had the highest average grain yield. This was verified especially in Caxias, Erechim, Passo Fundo and Ijuí, with average grain yields above 2,000 kg ha^{-1}, higher than the average yield for the State (1,860 kg ha^{-1}). The regions with average yield lower than 1,700 kg ha^{-1} (Bagé and Pelotas) were characterized by comparatively lower NDVI values.

For the average of the State, the periods with the highest percentage of planted area in the sub-periods of flowering, grain filling and maturation are indicated by arrows (Figure 5) and show consistency with expectations in terms of green biomass accumulation by grain producing crops.

The vegetative development is characterized by the continuous increase in green biomass, up to a maximum value. During the vegetative growth there is the formation of the photosynthetic apparatus of the plant and the determination of the potential number of meristematic buds in which the reproductive structures will develop (Thomas & Costa, 2010). In general, the maximum green biomass accumulation occurs in the period close to flowering. In soybean, induction of flowering takes place by

Table 1. Mean values and standard deviation of NDVI of the regions, in the subperiods and harvests studied. Period from 2000/2001 to 2009/2010

Location/Period	Mean NDVI	Standard deviation
Regions		
Caxias	0.709A	0.144
Ijuí	0.704A	0.181
Erechim	0.702A	0.164
Passo Fundo	0.693A	0.174
Santa Rosa	0.689A	0.170
Estrela	0.688A	0.117
Santa Maria	0.669AB	0.143
Bagé	0.626BC	0.141
Pelotas	0.613C	0.149
Subperiod		
Flowering	0.823 A	0.039
Grain filling	0.718 B	0.101
Maturation	0.490 C	0.055
Harvests		
2000-01	0.670 AB	0.163
2001-02	0.693 AB	0.126
2002-03	0.715 A	0.147
2003-04	0.676 AB	0.162
2004-05	0.602 C	0.130
2005-06	0.687 AB	0.168
2006-07	0.703 A	0.164
2007-08	0.687 AB	0.163
2008-09	0.652 B	0.172
2009-10	0.683 AB	0.154

Different uppercase letters in the same column indicate significant differences by Tukey's test ($p < 0.05$) between regions, subperiods or harvests.

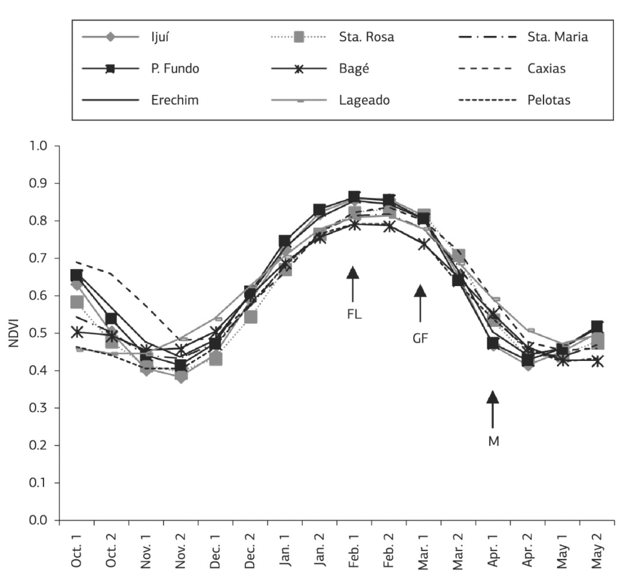

Figure 5. Average NDVI profiles of the areas planted with soybean in the Rio Grande do Sul State indicating the fortnight at which it was reached the maximum percentage of planted area in each subperiod (FL: flowering; GF: grain filling; M: maturation). Period from 2000/2001 to 2009/2010.

the combined response of the plant to photoperiod and air temperature, thus starting the reproductive period (Thomas & Costa, 2010). In this study, the average date of flowering was in the first half of February, when the NDVI values were close to the maximum. The analysis of the maximum NDVI value must consider the effect of saturation of the index, which has been extensively characterized (Jensen, 2009), which can restrict the sensitivity of the index in detecting variations of green biomass. In most regions, the NDVI value associated with the flowering subperiod was above 0.8 (Figure 6a-d), differing from the NDVI of the other two subperiods of the cycle (Table 1).

The grain filling subperiod is characterized by the reduction in green biomass, given leaf yellowing as a consequence of the reallocation of nutrients, nitrogen compounds and carbohydrates from leaf, stem, and branches to grains (Thomas & Costa, 2010). The average NDVI of this subperiod was lower than in flowering (Table 1). This was the subperiod with the greatest variability in NDVI values, as evidenced by box plots (Figure 6b-d). The variability observed in NDVI values between harvests are possibly associated with the differences in cycle of cultivars and weather conditions determining the grain moisture loss, until they reach harvest maturity, which, for the soybean crop is between 13% and 15% (Thomas & Costa, 2010).

In turn, the physiological maturity occurs when ends the accumulation of dry matter in soybeans and, from this stage, the leaves fall and the stem, branches, legumes and grains reduce the moisture content (Thomas & Costa, 2010). The physiological maturity occurred in March; in the NDVI/MODIS temporal profile, there was a reduction in NDVI values in relation to subperiods of flowering and grain filling (Figure 5), assuming values below 0.5 (Table 1). The lowest NDVI values were registered in April, coinciding with the harvest of soybean crops in the analyzed regions, with a low variability among crops for NDVI values (Figure 6c).

Similar results are found in the literature, which support the hypothesis tested in this study of relating the NDVI temporal profile of crops that occupy large areas to subperiods of their cycle. For cool season cereals, NDVI/MODIS temporal profiles obtained through crop mask and unsupervised classification were used in the identification of agricultural areas in the Rio Grande do Sul State (Junges & Fontana, 2009), showing consistency with the wheat crop calendar. For the sugar cane crop, Moraes (2013) also identified the stages of cultivation using MODIS/NDVI images.

In addition, it was also possible to detect significant differences between the analyzed harvests (Table 1), which according to previous studies (Fontana et al., 1998; Jacóbsen et al., 2003) are mainly associated with water stress. The reduction of green biomass in years of water deficit can be evaluated when analyzing two contrasting harvests: 2002/2003 (no water deficit) and 2004/2005 (water deficit). In almost all regions, given the favorable condition of rainfall in the 2002/2003 harvest (cumulative rainfall in January, February and March

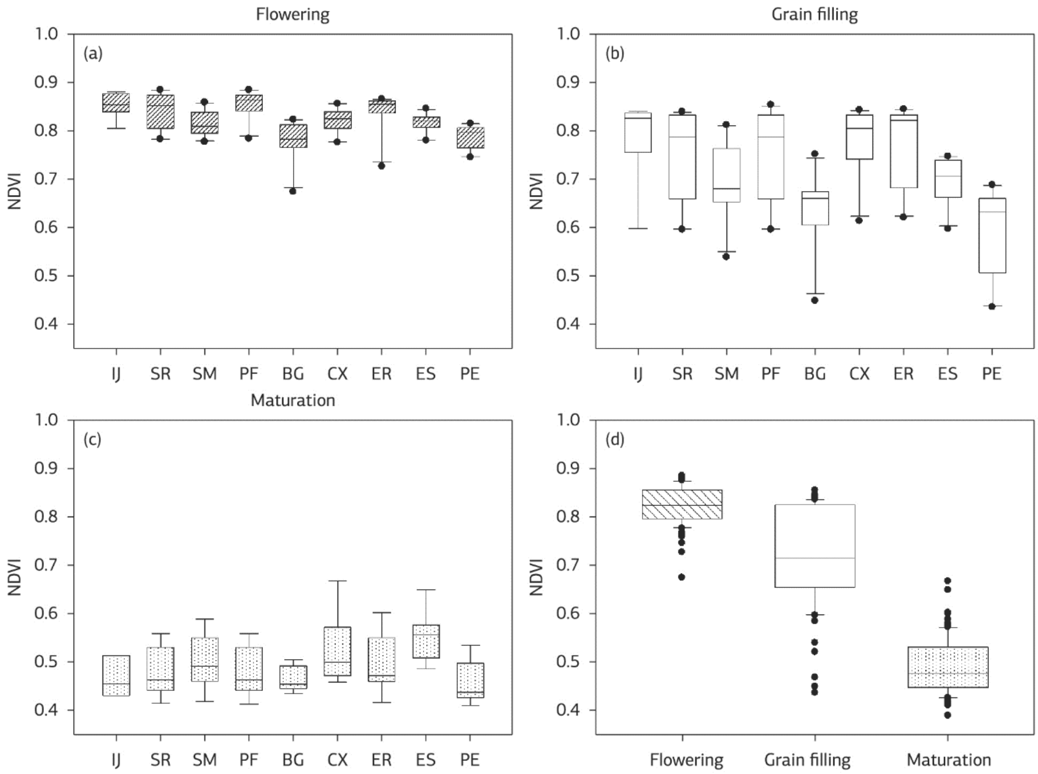

Figure 6. Box plots of NDVI data of the areas planted with soybean in nine regions of EMATER (RS) (a, b and c), and the average of the Rio Grande do Sul State (d), in the period from 2000 to 2010. The letters in x-axis represent the regions (Ijuí), SR (Santa Rosa), SM (Santa Maria), PF (Passo Fundo), BG (Bagé), CX (Caxias), ER (Erechim), ES (Estrela) and PE (Pelotas).

of about 710 mm), the NDVI/MODIS temporal profiles (Figure 4) were characterized by values above the average, especially in February and March, which concentrate the grain filling subperiod. In the 2004/2005 harvest, given the unfavorable condition of rainfall (210 mm in January, February and March), plant growth was restricted, and the NDVI values were below from the other harvests. Losses in soybean production in these two harvests were, respectively, 0.06% and 79.09% (EMATER, 2008). Whereas the average production of soybean in the Rio Grande do Sul State is about 7.2 million tons (average from 2000 to 2010), the loss occurred in 2004/2005 was approximately 5.6 million tons. Considering the price of soybeans in R$ 60.00/bag of 60 kg (December 2014), the loss of grains determined a loss of R$ 5,600,000.00 for the Rio Grande do Sul State.

Each region, given the conditions of soil, climate and cultivation tradition, presents a distinctive temporal pattern, which enables to map, in near real time, the succession of subperiods of the soybean crop cycle. In order to illustrate the type of information that can be made available from the results obtained in this study, the three subperiods of the soybean crop for the 2008-09 harvest in the municipality of Cruz Alta have been mapped and are shown in figure 7.

First, the spatial distribution analysis of soybean production evidences the great economic, social and environmental importance of this municipality. On average (2000 to 2010), 174,550 ha are planted with soybean, which represents about 74% of the municipal territory (IBGE, 2013). The cultivation is not concentrated in specific sectors. This is a result of environmental conditions, especially soil and topography, favorable to this crop, combined with tradition in the cultivation of this oilseed.

Regarding the succession of subperiods of the cycle, there was consistency in the analysis. By quantifying the percentage of acreage in each subperiod on the dates shown in figure 7, demonstrates that in February1, 19.2% of the planted area was at flowering, in March1, 16.9% of the crops was at grain filling and in April 2, 16.3% was at physiological maturity. These percentages are very similar to those found for the average of soybean growing areas in the Rio Grande do Sul State (Figure 2). The advantage of this method is the possibility of achieving greater spatial detail. While EMATER (RS) provides an average data per region, MODIS images enable to obtain the soybean calendar for each pixel, municipality, region or State.

It is also observed that, in each of the dates, there are crops classified into distinct subperiods, but with much smaller area. This is expected given the variability among crops, which is due to management differences employed by the farmer, especially the sowing date and the type of cycle of the cultivar.

These analyses demonstrate the relevance and potential of information obtainable from the establishment of consistent relationships between data collected in surface

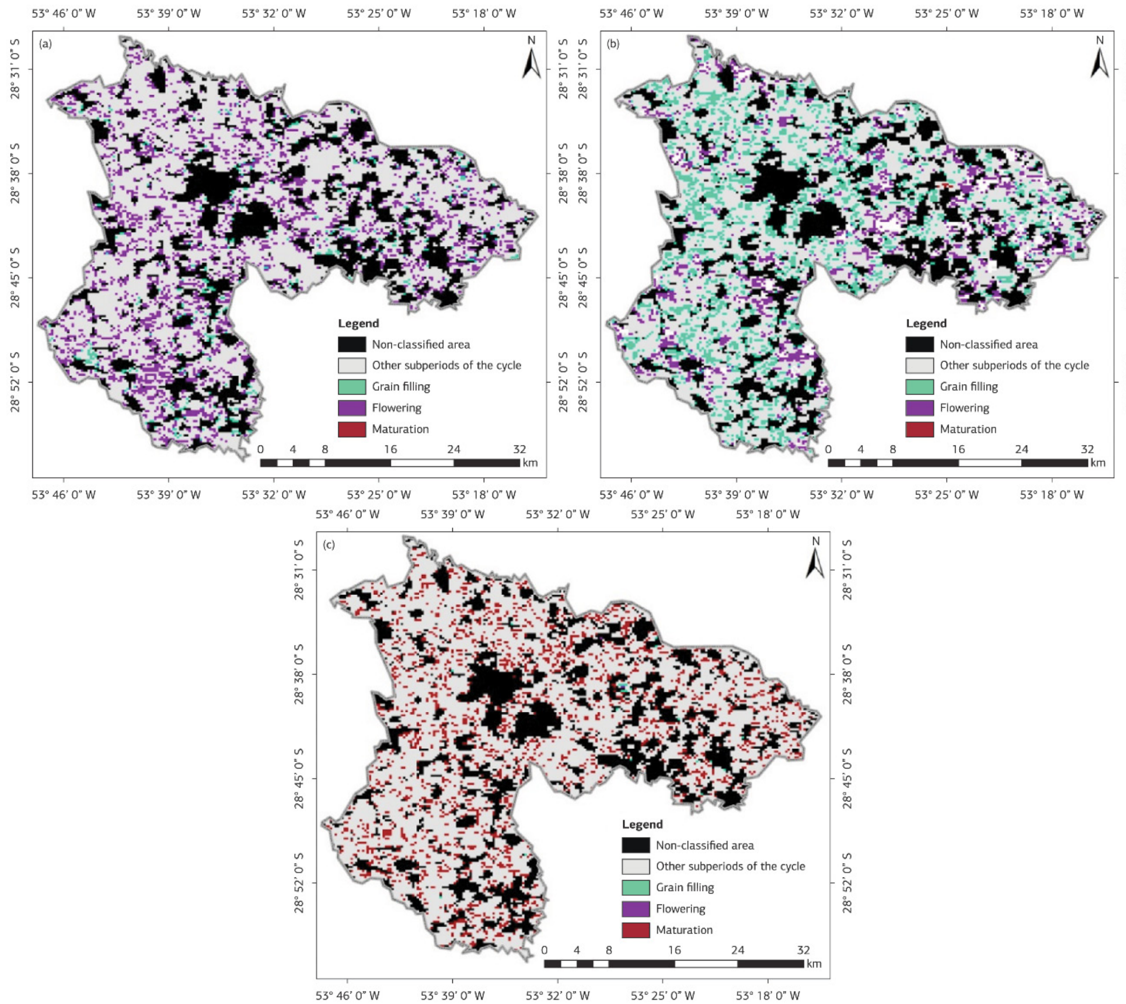

Figure 7. Identification of subperiods of the soybean crop cycle in: (a) February1, (b) March1 and (c) April2, in the municipality of Cruz Alta, 2008/2009 harvest.

and data generated from high temporal resolution image, which allow monitoring the producing areas. The availability of this information for crop monitoring systems is useful and represents an original contribution that can only be obtained from satellite images, especially MODIS sensor, NDVI product.

4. CONCLUSION

The NDVI temporal profiles, obtained from MODIS TERRA images, allow monitoring the temporal development of the soybean crop biomass and determining the occurrence of subperiods of flowering, grain filling and maturation.

Differences in NDVI values between harvests, regions and subperiods of the cycle evidence the sensitivity of this index in detecting the responses of soybean plants to environmental conditions.

Because NDVI data are generated from MODIS images, it is possible to create maps with information about the subperiods for all harvests and throughout the State, which enables greater temporal and spatial details compared to data currently available.

It is also emphasized the economic importance of information, in contrast to the reduced cost of obtaining it, since the distribution of MODIS images is free.

REFERENCES

Brasil. Ministério da Agricultura, Pecuária e Abastecimento – MAPA (2013). Zoneamento agrícola de risco climático. Brasília: MAPA. Recuperado em 4 de setembro de 2013, de http://www.agricultura.gov.br/politica-agricola/zoneamento-agricola.

Cunha, G. R., Barni, N. A., Haas, J. C., Maluf, J. R. T., Matzenauer, R., Pasinato, A., Pimentel, M. B. M., & Pires, J. L. F. (2001). Zoneamento agrícola e época de semeadura para soja no Rio Grande do Sul. Revista Brasileira de Agrometeorologia, 9, 446-459.

De Melo, R. W., Fontana, D. C., Berlato, M. A., & Ducati, J. R. (2008). An agrometeorological-spectral model to estimate soybean yield, applied to southern Brazil. International Journal of Remote Sensing, 29, 4013-4028. http://dx.doi.org/10.1080/01431160701881905.

EMATER (2008). EMATER. Porto Alegre: EMATER/RS - ASCAR. Recuperado em 4 de setembro de 2013, de http://www.emater.tche.br.

Fontana, D. C., Berlato, M. A., & Bergamaschi, H. (1998). Relação entre índice de vegetação global e condições hídricas no Estado do Rio Grande do Sul. Pesquisa Agropecuária Brasileira, 33, 1399-1405.

Fontana, D. C., Potgieter, A. B., & Apan, A. (2007). Assessing the relationship between shire winter crop yield and seasonal variability of the MODIS NDVI and EVI images. Applied GIS, Carlton, 3, 1-16.

Gusso, A., Formaggio, A. R., Rizzi, R., Adami, M., & Rudorf, B. F. T. (2012). Estimativa de áreas de cultivo de soja por meio de dados MODIS/EVI. Pesquisa Agropecuária Brasileira, 47, 425-435. http://dx.doi.org/10.1590/S0100-204X2012000300015.

Huete, A., Didan, K., Miura, T., Rodriguez, E. P., Gao, X., & Ferreira, L. G. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sensing of Environment, 83, 195-213. http://dx.doi.org/10.1016/S0034-4257(02)00096-2.

Instituto Brasileiro de Geografia e Estatística – IBGE. Sistema IBGE de Recuperação Automática – SIDRA, 2013. Sistema IBGE de recuperação automática: banco de dados agregados. Rio de Janeiro: IBGE. Recuperado em 22 de outubro de 2013, de http://www.sidra.ibge.gov.br/bda/tabela/listabl.asp?z=t&o=11&i=P&c=1612.

Jacóbsen, L. O., Fontana, D. C., & Shimabukuro, Y. (2003). Alterações na vegetação em macrozonas do Rio Grande do Sul associadas a eventos El Niño e La Niña usando imagens NOAA. Revista Brasileira de Agrometeorologia, 11, 361-374.

Jensen, J. R. (2009). Sensoriamento Remoto do Ambiente: uma perspectiva em recursos terrestres (J. C. N. Epiphanio, Trans.). São José dos Campos: Parêntese.

Johann, J. A., Rocha, J. V., Duft, D. G., & Lamparelli, R. A. C. (2012). Estimativa de áreas com culturas de verão no Paraná, por meio de imagens multitemporais EVI/Modis. Pesquisa Agropecuaria Brasileira, 47, 1295-1306. http://dx.doi.org/10.1590/S0100-204X2012000900015.

Junges, A. H., & Fontana, D. C. (2009). Avaliação do desenvolvimento das culturas de cereais de inverno no Rio Grande do Sul por meio de perfis temporais do índice de vegetação por diferença normalizada. Ciência Rural, 39, 1349-1355. http://dx.doi.org/10.1590/S0103-84782009005000114.

Mercante, E., Lamparelli, R. A. C., Uribeopazo, M., & Rocha, J. V. (2010). Modelos de regressão lineares para estimativa de produtividade da soja no Oeste do Paraná, utilizando dados espectrais. Engenharia Agrícola, 30, 504-517.

Monteiro, J. E. B. A. (2009). Agrometeorologia dos cultivos: o fator meteorológico na produção agrícola. Brasília: INMET. 530 p.

Moraes, R. A. (2013). Identification and classification of the annual crop stages in the Parana state through the use of MODIS/NDVI temporal profiles. Pesquisa Aplicada & Agrotecnologia, 6, 7-16.

Ponzoni, F. J., & Shimabukuro, Y. E. (2007). Sensoriamento remoto no estudo da vegetação. São José dos Campos: Parêntese. 127 p.

Rizzi, R., & Rudorff, B. F. T. (2007). Imagens do sensor MODIS associadas a um modelo agronômico para estimar a produtividade de soja. Pesquisa Agropecuaria Brasileira, 42, 73-80. http://dx.doi.org/10.1590/S0100-204X2007000100010.

Rudorff, B. F. T., Shimabukuro, Y. E., & Ceballos, J. C. (2007). O sensor MODIS e suas aplicações ambientais no Brasil (1 ed.). São José dos Campos: Parêntese. 425 p.

Santos, J. S., Fontana, D. C., Silva, T. S. F., & Rudorff, B. F. T. (2014). Identificação da dinâmica espaço-temporal para estimar área cultivada de soja a partir de imagens MODIS no Rio Grande do Sul. Revista Brasileira de Engenharia Agrícola e Ambiental, 18, 54-63. http://dx.doi.org/10.1590/S1415-43662014000100008.

Statistical Analyses System – SAS (2008). Statistical analyses system user's guide. Cary: Statistical Analysis Institute. Version 9.2.

Thomas, A. L., & Costa, J. A. (2010). Desenvolvimento da planta de soja e o potencial de rendimento de grãos. In A. L. Thomas, & J. A. Costa (Eds.), Soja: manejo para alta produtividade de grãos (p. 13-33). Porto Alegre: Evangraf.

Wagner, A. P. L., Fontana, D. C., Fraisse, C., Weber, E., & Hasenack, H. (2013). Tendências temporais de índices de vegetação nos campos do Pampa do Brasil e do Uruguai. Pesquisa Agropecuaria Brasileira, 48, 1192-1200. http://dx.doi.org/10.1590/S0100-204X2013000900002.