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Article

Remote Sensing Time Series to Evaluate Direct Land Use Change of Recent Expanded Sugarcane Crop in Brazil

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Abstract: The use of biofuels to mitigate global carbon emissions is highly dependent on direct and indirect land use changes (LUC). The direct LUC (dLUC) can be accurately evaluated using remote sensing images. In this work we evaluated the dLUC of about 4 million hectares of sugarcane expanded from 2005 to 2010 in the South-central region of Brazil. This region has a favorable climate for rain-fed sugarcane, a great potential for agriculture expansion without deforestation, and is currently responsible for almost 90% of Brazilian's sugarcane production. An available thematic map of sugarcane along with MODIS and Landast images, acquired from 2000 to 2009, were used to evaluate the land use prior to the conversion to sugarcane. A systematic sampling procedure was adopted and the land use identification prior to sugarcane, for each sample, was performed using a web tool developed to visualize both the MODIS time series and the multitemporal Landsat images. Considering 2000 as reference year, it was observed that sugarcane expanded: 69.7% on pasture land; 25.0% on annual crops; 0.6% on forest; while 3.4% was sugarcane land under crop rotation. The results clearly show that the dLUC of recent sugarcane expansion has occurred on more than 99% of either pasture or agriculture land.

Keywords: LUC; biofuels; monitoring; MODIS

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1. Introduction

The use of biofuels to mitigate greenhouse gases (GHG) emissions and consequently prevent the global warming potential has been widely discussed [1]. The production of biofuel from sugarcane is well established in Brazil [2] and presents a great potential to mitigate GHG due to its high efficiency [3–5]. The growing demand of sugarcane for ethanol production, especially after 2003 with the advent of the flex cars in Brazil, has caused a rapid expansion of this crop during the last years [6]. However, several discussions on the sustainable sugarcane production and its actual potential to mitigate GHG have been reported in the literature [7,8].

The direct land use change (dLUC) from pasture or other agricultural crops to sugarcane can contribute to local climate cooling [9]. With regard to food security, Martinelli *et al.* [10] discussed that the reduction of pasture land as a consequence of sugarcane expansion can be compensated by increasing the efficiency of livestock production. Furthermore, Mueller *et al.* [11] concluded that the recent food price increase is not correlated to the increased demand of biofuels.

For Hill *et al.* [12], the potential benefits of biofuels to reduce carbon emissions are highly dependent on the LUC triggered by the expansions of biocrops. Kim *et al.* [13] pointed out that crop management practices have a significant impact on carbon emissions as was also reported by Macedo *et al.* [14] and Figueiredo & La Scala Jr. [15], specifically for the sugarcane case. Indirect LUC (iLUC) impacts of sugarcane expansion have been reported in the literature (e.g., Kim *et al.* [13] and Lapola *et al.* [16]), but present many uncertainties due to the complexity involved in its definition and evaluation. However, the dLUC impacts can be accurately quantified by using remote sensing satellite images [17].

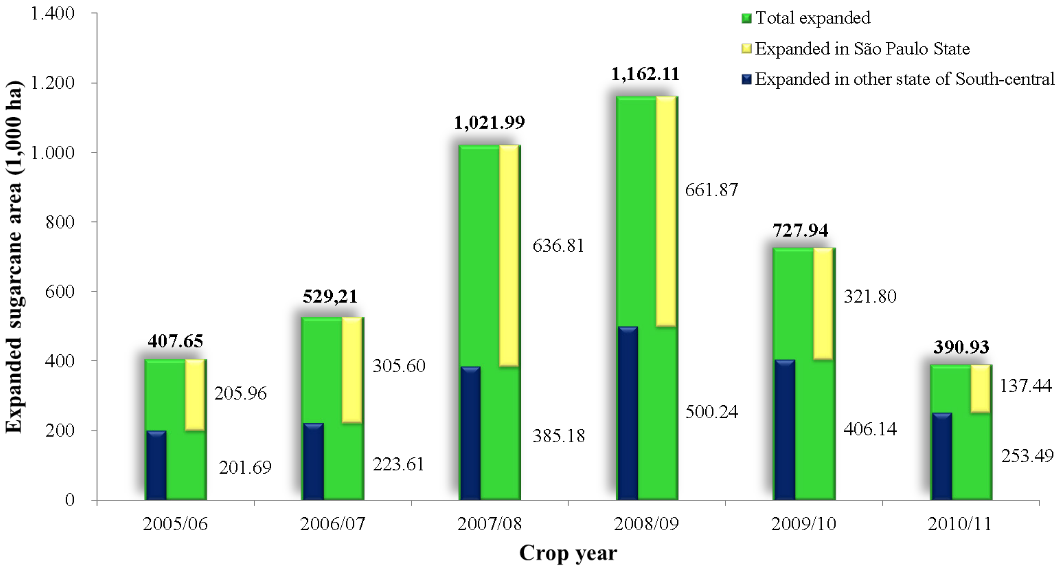
These images are acquired by sensors on board of satellites. The images present different characteristics, especially in terms of spatial and temporal resolutions. Several countries that own remote sensing satellites have recently adopted a policy to freely distribute these images through the Internet. This policy has dramatically increased the number of users and also the applications in the field of Earth observation, that otherwise would not have been possible due to the often prohibitive cost of the remote sensing images for environmental monitoring applications. Examples of countries that have adopted this policy are the USA, which, since 2000, has freely been distributing images from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on board of Terra and Aqua satellites for the entire terrestrial globe; and Brazil, which, in 2006, started to deliver through the Internet images from the China-Brazil Earth Resource Satellite (CBERS) and Landsat satellites over its own territory. Considering the enormous amount of freely available remote sensing images; the huge area of the South-central region of Brazil where sugarcane has rapidly expanded over the last decade; and the complexity of the aspects involved in the monitoring of LUC, this work aims at using satellite images from sensors with different spatial and temporal resolutions available on the Internet in order to quantify the dLUC observed during the first decade of the 21st century which was triggered by the increased demand of sugarcane for ethanol production.

2. Materials and Methods

2.1. Study Area

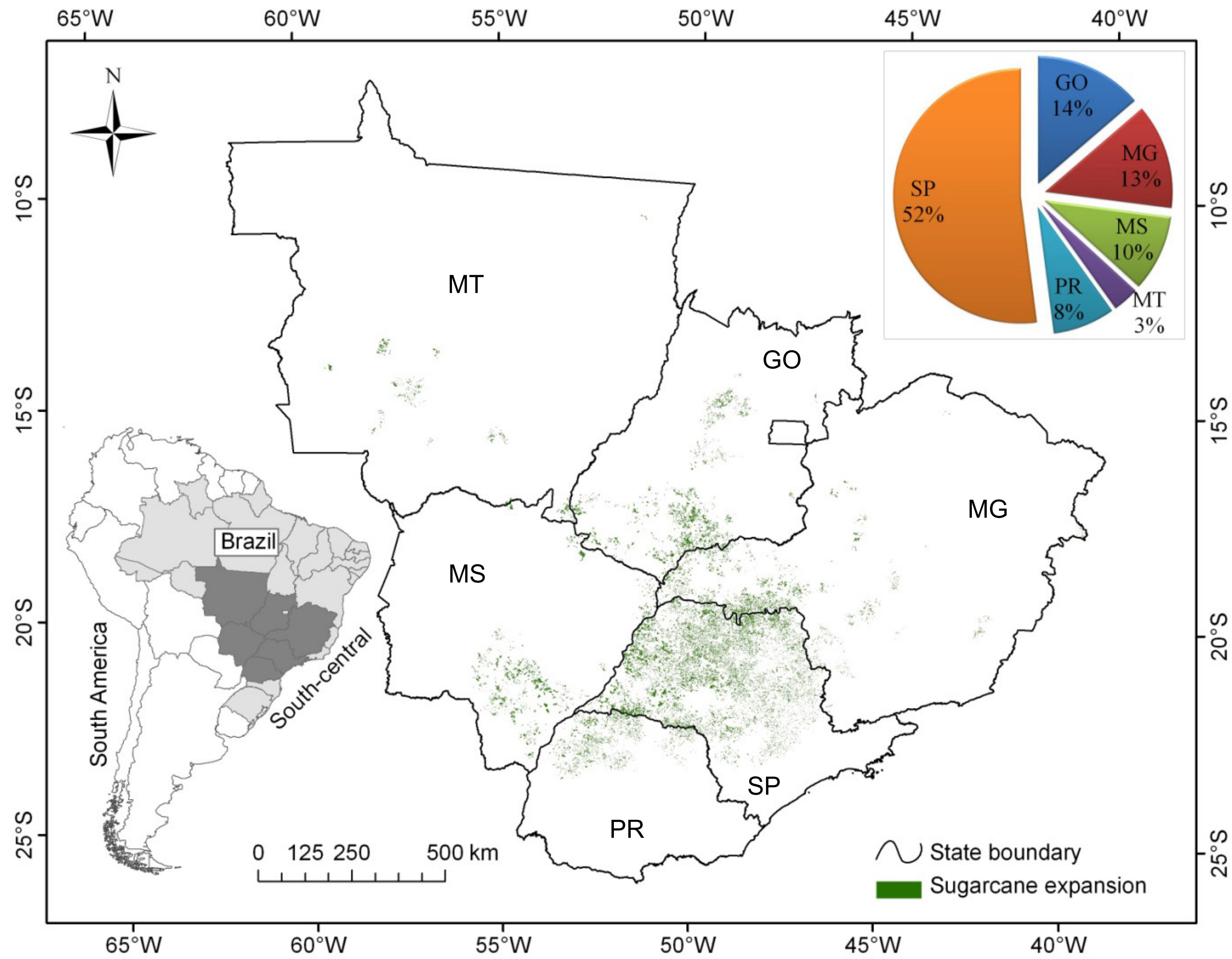
The study area comprises the South-central region of Brazil (states of: Goiás – GO; Mato Grosso – MT; Mato Grosso do Sul – MS; Minas Gerais – MG; Paraná – PR; and São Paulo – SP) currently responsible for 90% of the sugarcane production for sugar and ethanol in Brazil [18]. With the beginning of the production of flex cars by the Brazilian automobile industry in 2003 a substantial expansion of about 4.24 million hectares of sugarcane area was observed in this region from 2005 to 2010 [19]. However, it is likely that this increase could have been even bigger had it not been for the 2008 world crisis, which inhibited several new investments in the sucro-energy sector [20] so that the expansion rate of new sugarcane plantations was significantly reduced as illustrated in Figure 1. On the other hand, the demand for ethanol in the internal market, and the demand for sugar in the external market continued to increase independently of the world crises resulting in a shortage of ethanol since 2010 to supply the Brazilian market. It is estimated that this shortage will only be solved by 2013 through a new boom of sugarcane plantation that should start in 2012.

Figure 1. Expansion of sugarcane in South-central Brazil from crop year 2005/06 to 2010/11, highlighting São Paulo State.



In the South-central region of Brazil, São Paulo State has long been the major sugarcane producer, but recently other states such as Mato Grosso do Sul and Goiás have significantly increased their sugarcane areas. Furthermore, these states have huge available areas for agricultural use; while São Paulo State is already covered with 21.7% of its territory with sugarcane and its options for expansion have become more and more limited. In 2005 São Paulo State was responsible for 72.6% of the sugarcane area in the South-central region while in 2011 its share went down to 62.3% due to the sugarcane area increase in other states of the region. Figure 2 illustrates the expanded sugarcane area from 2005 to 2010 mapped with the use of remote sensing images [6,21].

Figure 2. Study area emphasizing the expanded sugarcane area from crop year 2005/06 to 2010/11 in the South-central region of Brazil (states of: Goiás–GO; Mato Grosso–MT; Mato Grosso do Sul–MS; Minas Gerais–MG; Paraná–PR and São Paulo–SP). The states of Rio de Janeiro (RJ), Espírito Santo (ES), Santa Catarina (SC) and Rio Grande do Sul (RS) are also part of this region; however, sugarcane expansion was not significant in these states during the observed period.



2.2. Materials

Materials used in this study were: *(i)* an available thematic map of sugarcane with the expanded areas for crop years 2005/06 to 2010/11 for São Paulo State and crop years 2007/08 to 2010/11 for the other sugarcane producing states in the South-central region (Figure 2); *(ii)* 1,184 Landsat satellite images acquired between 2000 and 2009 over the sugarcane areas in the South-central region (50 different path/row); and *(iii)* time series of the MODIS sensor on board of the Terra satellite for the period of 2000 to 2010 [22].

2.3. Methods

The analysis of the dLUC dynamic from 2000 to 2009 in the South-central region was carried out considering the sugarcane expansion observed for São Paulo State from crop years 2005/06 to 2010/11; and for the other states of the region from crop years 2007/08 to 2010/11 since the major expansions by state were observed during these crop years (Figure 1). The original sugarcane map of the sugarcane expansion areas was available in vector format, and was re-sampled and converted to raster format with spatial resolution of 250 × 250 m in order to be compatible with the MODIS image resolution. This conversion resulted in a map with 104,583 elements (N) of "pure pixels" of sugarcane. Based on these elements a systematic sampling [23] was performed selecting a sample (1%) with 1,046 elements (n). The first element was randomly selected and served as reference for the remaining elements, by adding 100 to each new selected element, until the total number of elements was selected. A systematic sampling assures that the entire geographic region will be represented and that the amount of elements will be selected considering its spatial distribution [23].

The objective of the sampling is to estimate the area proportion of each land use class (p_c) prior to the sugarcane crop, given by

$$\hat{p}_c = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{1}$$

where y represents the sample whose identifier varies from i to n, y_i will be one if it belongs to class c, otherwise it will be zero; $\hat{p}_c$ is the estimated proportion of samples that belong to class c. The expansion of the area for each class a_c is estimated by $\hat{a}_c = N\,\hat{p}_c$.

The variance of the estimates for each class (v_c) was estimated by

$$\hat{v}_c = n\,\hat{p}_c\,\hat{q}_c\,\frac{N-n}{N-1} \tag{2}$$

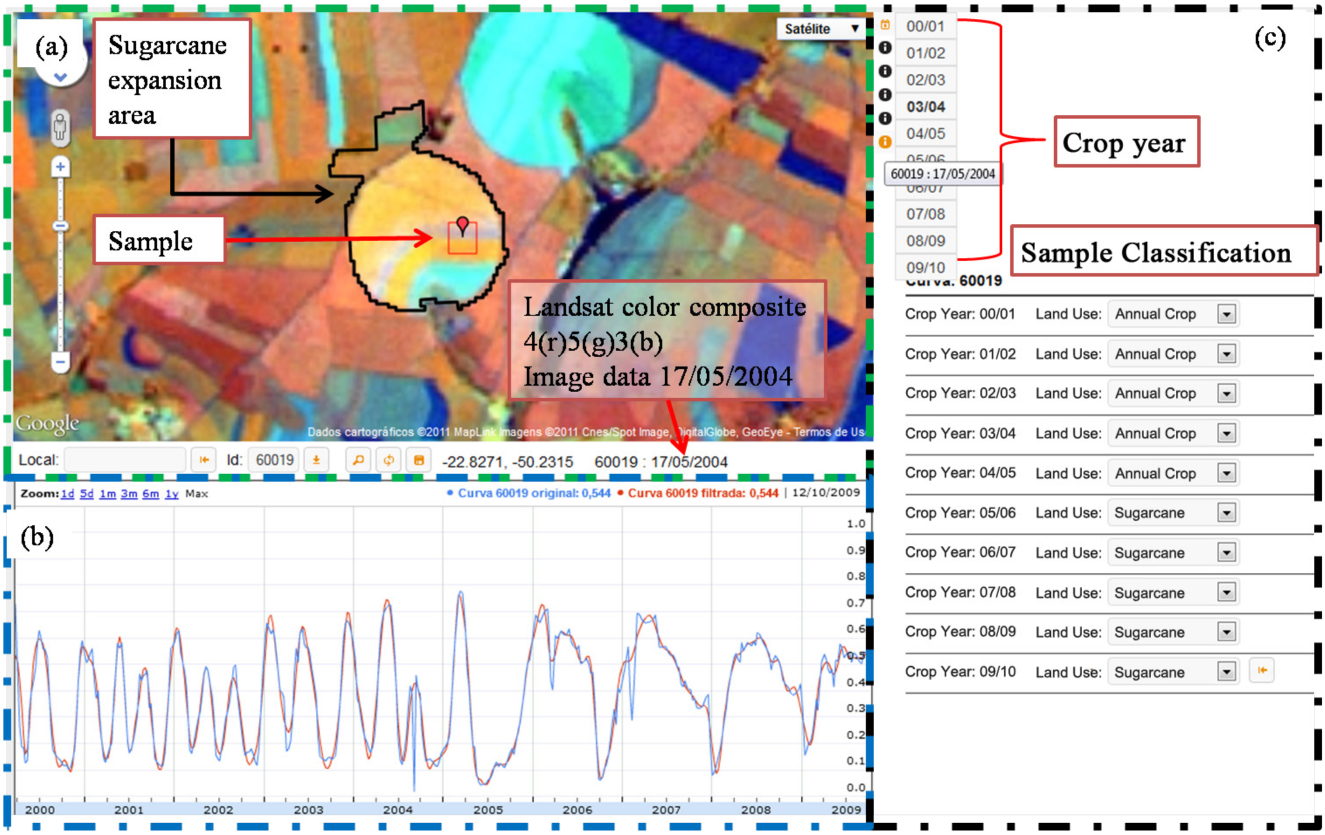
where $\hat{q}_c = 1 - \hat{p}_c$; whose confidence interval for each class (CI_c) is estimated by

$$\widehat{CI}_C = \pm Z_{\alpha/2}\sqrt{\hat{v}_c} + \frac{1}{2n} \tag{3}$$

where Z is the critical value of the standardized normal probability density function, in terms of the confidence interval ($\alpha/2$).

The classification of the land use prior to the sugarcane crop was carried out by the team of the Laboratory of Remote Sensing in Agriculture and Forestry (LAF), at INPE, using visual image interpretation combining the use of the relatively high spatial resolution of Landsat images with the high temporal resolution of MODIS images. A web tool, illustrated in Figure 3, was specially developed to integrate the 1,046 sampled elements with multitemporal Landsat images and MODIS time series. This allowed the interpreter to assign year by year, from 2000 to 2009, each one of the elements to one of the following classes: *annual crop*, *citrus*, *forest*, *pasture* and *sugarcane*.

Figure 3. The web tool for combined analyses of MODIS time series and multitemporal Landsat images associated to a classification scheme. (**a**) Virtual globe integrated with Landsat color composite image. The small red square with the balloon corresponds to the pixel of the MODIS time series presented in (**b**). In (**c**) are displayed the crop years for selection of the Landsat image to be visualized in (**a**); e.g., Landsat image from 17 May 2004. In the lower part of (**c**) is displayed the classification legend that was assigned by the interpreter in each crop year. For this particular sample it can be observed that from crop year 2000/01 to 2004/05 the land use was *annual crop* and from 2005/06 on it became *sugarcane*.



The Landsat images available on the web tool were acquired yearly from 2000 to 2009 during the rainy season (October through March) and during the dry season (May through August). To interpret the samples a small part of each Landsat image was selected covering an area of 15 × 15 km around the area of interest as illustrated in Figure 3.

The MODIS time series used in the web tool was constructed based on data from the collection 5 of the MOD09 product (8 day composition) available at the portal of the Warehouse Inventory Search Tool WIST NASA [24]. The pixel selection process for the MOD09 product takes into account the parameters obtained from the MOD35 and MOD04 products in order to select cloud free pixels with lowest view angle. Information of the Quality Assessment (QA) product for the daily acquired images from the MOD09GHK product is also used in this process [25]. Even though this selection process eliminates most of the unwanted information present in the raw MODIS data, it is still noisy, especially for visualization purpose in the form of graphs. Therefore, data from the MOD09 product were further processed following the method proposed by Freitas *et al.* [26] using two additional filters to improve the visual quality of the time series presented in the form of graphs. The first filtering consists of withdrawing pixels with both view angle greater than 30° and spectral reflectance greater than 10% in band 3 (blue), as suggested by Sakamoto *et al.* [27]. Afterwards, the time series were linearly interpolated at daily scale using the MODIS product day-of-year, as suggested by Thayn & Price [28]. The second additional filtration proposed by Sakamoto *et al.* [27] uses the mother wavelet DB8 [29].

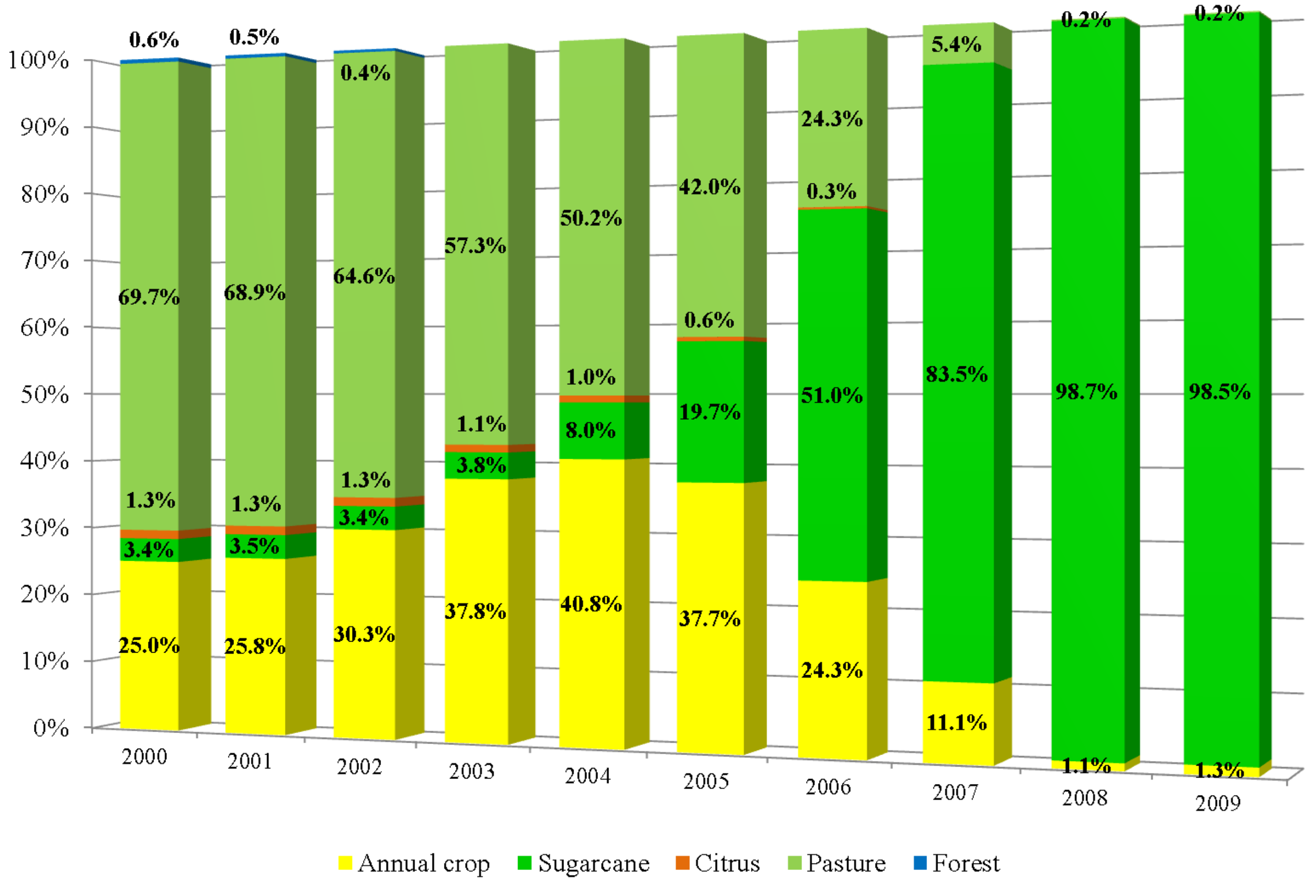
Eventually, the filtered data, coming from the MODIS images acquired from 2000 to 2009 over the entire study area, were used to calculate the vegetation index named Two-Band Enhanced Vegetation Index (EVI2) [30] that was the ultimate representation of the MODIS images in the time series presented in the web tool (Figure 3). The time series graphs in blue and red color, presented in Figure 3, are respectively from the first (without wavelet) and second (with wavelet) additional filtration carried out by Freitas *et al.* [26]. The two time series are quite similar and the interpreter could choose which one provides the best information to classify the land use for the selected elements.

It is worth mentioning that, on the web tool, the MODIS EVI2 time series are only available for each selected element (sample) of 250 × 250 m to be classified since there is no need to spatially contextualize those elements, but rather observe the vegetation index (EVI2) behavior over time which should help to understand the LUC history of each particular element. However, for the Landsat images it is fundamental to spatially contextualize each selected element so that the image can actually help to correctly classify the LUC; therefore, each selected element was surrounded by an area of 15 × 15 km. After the classification of the 1,046 selected elements by the interpreters, the conversion metrics were obtained using descriptive statistics.

3. Results and Discussion

Figure 4 presents the result of the dLUC dynamic analysis observed in the South-central region of Brazil during the first decade of the 21st century in response to the recent sugarcane expansion that was mainly triggered by the increased demand of sugarcane to produce ethanol. From the total sugarcane area expanded in São Paulo State since 2005 and in the rest of the South-central region since 2007, it can be noticed that in the year 2000, 69.7% (±2.8%) of this area was *pasture* and 25.0% (±2.6%) was *annual crop* which together account for 94.7% of the dLUC due to sugarcane. An area equivalent to 3.4% (±1.1%) was already under *sugarcane* cultivation, back in 2000, which correspond to the sugarcane fields under renovation in 2005 in São Paulo and in 2007 for the remaining states. Still in regard to the year 2000, 1.3% (±0.07%) of sugarcane expanded over *citrus*. The dLUC from *citrus* to *sugarcane* was only observed in São Paulo State once no significant citrus plantations are found outside São Paulo within areas under the influence of sugarcane plantation. Eventually, 0.6% (±0.05%) of the sugarcane expanded over areas that were *forest* in 2000 corresponding to an area of 16.8 thousand hectares. In a survey carried out by the Brazilian Supply Company (CONAB) [31] at 343 sugar and ethanol plants to evaluate the dLUC of expanded sugarcane areas in crop year 2007/08 it was observed that 66% of sugarcane expanded on pasture land and 29% on annual or perennial crops, and the other 5% came from other classes not specified in the paper; however, the base line year used as reference for the dLUC evaluation was not reported. Nassar *et al.* [17] used Landsat images to evaluate the dLUC of sugarcane expansion in crop years 2006/07 and 2008/09. They observed that 51% expanded on pasture; 48% on annual or perennial crops and 1% on cultivated or natural forest.

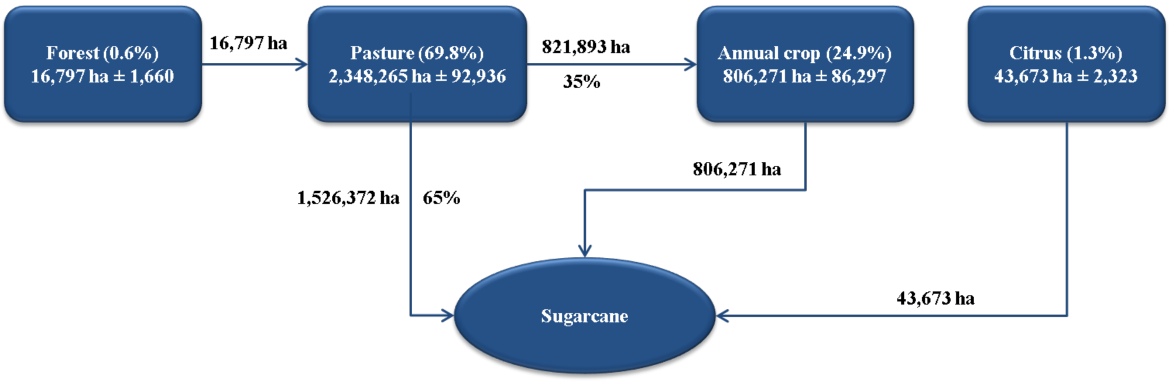
Figure 4. The direct land use change (dLUC) dynamic for sugarcane expansion in the South-central region of Brazil over the period of 2000 to 2009.



Analyzing the results of the dLUC dynamic presented in Figure 4, one can notice that the *annual crop* area in 2000 slightly increased between 2001 and 2006 indicating that part of the *pasture* land converted to *sugarcane* was firstly converted to *annual crop*. This is a commonly adopted management practice to improve the physic-chemical soil characteristics of the degraded pasture land [32].

Figure 5 shows that from the total *pasture* land in 2000, 65% was directly converted to *sugarcane*, and 35% was firstly converted to *annual crop* explaining the gradual increment of this class between 2001 and 2006 (Figure 4). Figure 5 also shows that the *forest* class was initially converted to *pasture* and later to *sugarcane*; while the conversion of both *annual crop* and *citrus* to *sugarcane* was direct.

Figure 5. The conversion process of the different land use classes to sugarcane. The values inside the boxes represent the estimated area of the land use classes in 2000 that were gradually converted to sugarcane until 2010.



These numbers agree with the work published by Lapola *et al.* [16] in regard to the small impact of sugarcane expansion on deforestation; however, they disagree with the work published by Naylor *et al.* [33] in regard to the significant impact of sugarcane on biodiversity, since more than 99% of the recent expanded sugarcane area was on land occupied prior to 2000 with either pasture or agriculture. Considering that the majority of the pasture land in Brazil is somehow degraded [34], then the major observed LUC from pasture to sugarcane for ethanol production might have an even more significant contribution not only in the mitigation of GHG [35–37] but also in the cooling of local climate according to the conclusion of the study made by Loarie *et al.* [9].

The dLUC analysis showed that sugarcane expanded on either pasture or agricultural land. Therefore, it is expected that the reduced pasture land will either reduce the cattle herd or induce deforestation for new land availability. However, for the Brazilian case, the intensification of pasture land use due to increased livestock efficiency has released much land for crop production, and this will continue during the next decades, so that in theory no further deforestation should be needed to accommodate the demand of new land for either food or biofuel production [38,39]. For example, in São Paulo State the cattle herd carrying capacity went from 1.00 head per hectare in 1975 to 1.85 heads per hectare in 2006, and although the pasture land was significantly reduced by 4.4 million hectares the cattle herd increased by 1.4 million heads [18]. Also, the South-central region experienced both a loss of 24.1 million hectares of pasture lands and an increase of 45.3 million heads of cattle just by increasing the carrying capacity from 0.58 to 1.23 heads per hectare from 1975 to 2006 [18].

Similarly, the Brazilian grain production has continuously grown over the last 36 years at an annual rate of 3.8%, which can be attributed to the annual growth rate of crop yield (2.5%) and also to the increase in cropped area by an annual rate of 1.3% [40]. It is expected that under a competitive economy the productivity gains should continue over time representing a 50% increase in grain production for the next 17 years. Another relevant aspect to be considered in the impact of biofuels on LUC is related to environmental protection measures imposed by the consumer market (e.g., Soy Moratorium [41]), not to mention the large number of certification initiatives that are extremely concerned with the effects of biofuels on LUC.

4. Conclusions

The remote sensing satellite images at different spatial and temporal resolutions were useful to evaluate the direct land use change observed during the last decade triggered by the increased demand of sugarcane for ethanol production in the South-central region of Brazil. More than 99% of the recent sugarcane expansion for ethanol and sugar production was either on pasture or agricultural land. The loss of pasture land to sugarcane was largely compensated by the growing livestock production efficiency in Brazil.

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Conflict of Interest

The authors declare no conflict of interest.

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