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Article

Studies on the Rapid Expansion of Sugarcane for Ethanol Production in São Paulo State (Brazil) Using Landsat Data

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Abstract: This study's overarching aim is to establish the areal extent and characteristics of the rapid sugarcane expansion and land use change in São Paulo state (Brazil) as a result of an increase in the demand for ethanol, using Landsat type remotely sensed data. In 2003 flex fuel automobiles started to enter the Brazilian consumer market causing a dramatic expansion of sugarcane areas from 2.57 million ha in 2003 to 4.45 million ha in 2008. Almost all the land use change, for the sugarcane expansion of crop year 2008/09, occurred on pasture and annual crop land, being equally distributed on each. It was also observed that during the 2008 harvest season, the burned sugarcane area was reduced to 50% of the total harvested area in response to a protocol that aims to cease sugarcane straw burning practice by 2014 for mechanized areas. This study indicates that remote sensing images have efficiently evaluated important characteristics of the sugarcane cultivation dynamic providing quantitative results that are relevant to the debate of sustainable ethanol production from sugarcane in Brazil.

Keywords: cropland; cultivated area; type of harvest; land use change

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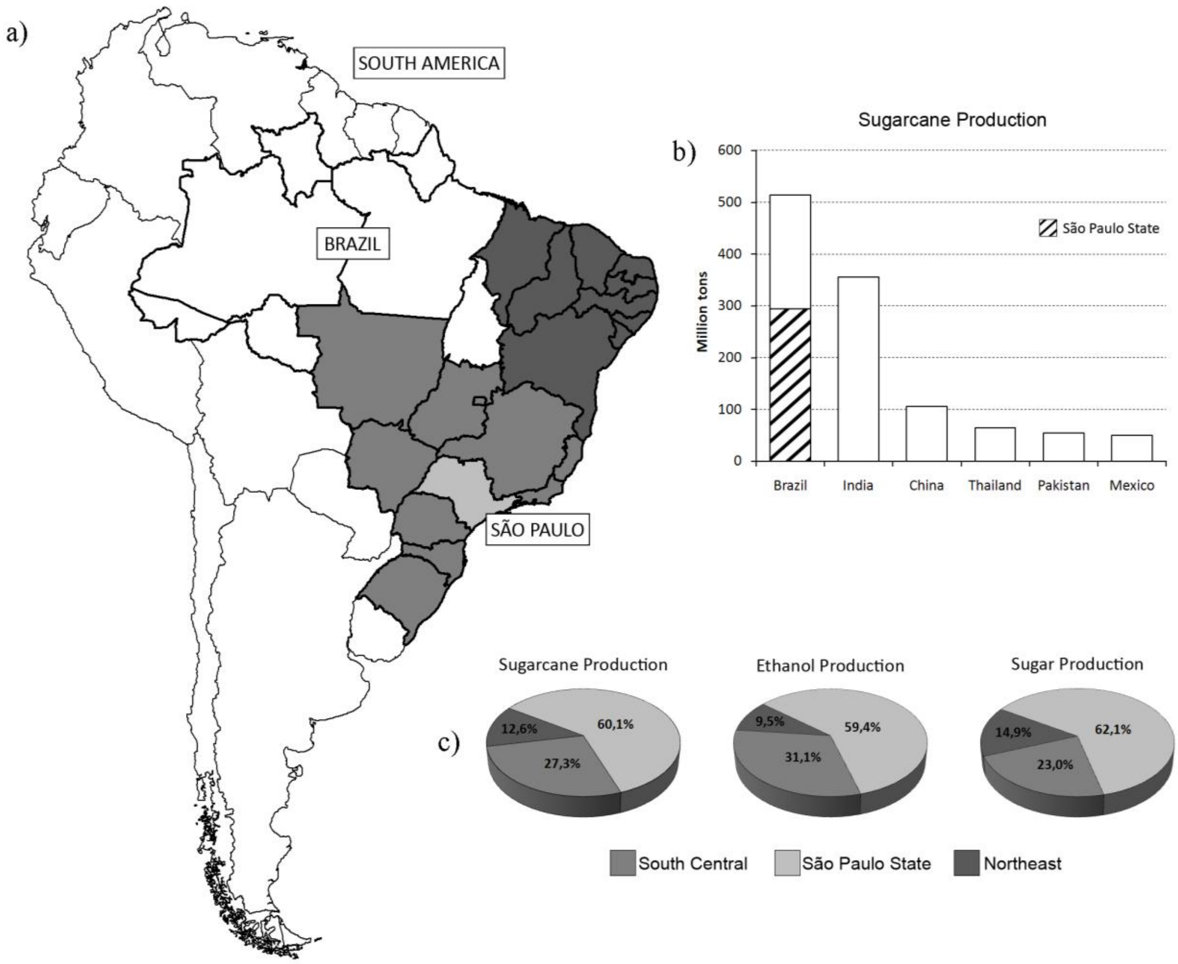
1. Introduction

The search for alternatives to mitigate greenhouse gas emissions has indicated the use of biofuels as a viable option, since they meet sustainability criteria. Brazil has a vast experience using ethanol, produced from sugarcane as an automotive fuel or gasoline additive [1,2].

Brazil is the world's largest sugarcane producer, and its production is concentrated in the South-Central states and Northeast regions, mainly in the South-Central region, particularly in the state of São Paulo. Figure 1 illustrates the representation of each region as to sugarcane, ethanol and sugar production for the 2007/08 crop year in addition to presenting a comparison among the six largest sugarcane producers. According to FAO [3], for the 2007/08 crop year, Brazil produced 45% more than India which is the world's second largest sugarcane producer (Figure 1b). In Brazil, the state of São Paulo is responsible for about 60% of sugarcane, ethanol and sugar production (Figure 1c) [4]. In terms of sugarcane production, this is equivalent to 83% of India's production, and it also represents an output larger than that of the four other major world producers combined (China, Thailand, Pakistan and Mexico).

Figure 1. (**a**) Location of the South-Central region (highlighting São Paulo state) and the Northeast region of Brazil, (**b**) the six largest sugarcane producers in the world for the 2007/08 crop year, (**c**) percentage of sugarcane, ethanol and sugar production from Northeast and South-Central regions of Brazil, with São Paulo state presented separately.



In order to meet the increasing domestic demand for ethanol, due to the recent and substantial increase in the fleet of flex fuel cars, new areas for sugarcane have been cultivated on a large scale. In the 2006/07 and 2007/08 crop years alone, cultivation in new areas reached 1.55 million hectares (ha) within the South-Central region of Brazil (www.dsr.inpe.br/canasat/). As a direct consequence of this expansion, sugarcane cultivation has replaced pasture and agricultural areas in similar proportions [5] and, despite the considerable increase in mechanical harvesting, manual harvesting, which requires straw burning, is still widely practiced [6]. In addition to this increasing domestic demand, Brazil could become a major exporter of ethanol, once it can break the barriers imposed by the socio-environmental certifications proposed by potential importing countries [7,8]. To obtain certification, Brazil will have to meet some criteria, such as: (i) not to replace areas designated for food production and biodiversity conservation with sugarcane, and (ii) to eliminate the practice of straw burning prior to harvesting [9,10].

In this sense, the Brazilian government has recently conducted a study to establish Sugarcane Agro-ecological Zoning which considers environmental, economic, and social aspects to guide both sustainable expansion of sugarcane production and investments in the biofuel sector. The Secretary of Environment of São Paulo State also signed an agro-environmental protocol in 2007 with the ethanol agro-industry sector. This protocol establishes the gradual elimination of burning practices by 2014 for mechanized areas (slope ≤ 12%) and by 2017 for non-mechanized areas (slope > 12%; http://homologa.ambiente.sp.gov.br/etanolverde/english.asp). Similar measures have also been adopted by other states in the South-Central region of Brazil; which in addition to being the largest sugarcane producers (Figure 1), have a great availability of pasture land with smooth relief (slope ≤ 12%). Such characteristic may prevent areas designated for food production from being replaced by sugarcane, in addition to promoting harvest mechanization in order to eliminate the practice of straw burning. Nevertheless, the effectiveness of these measures is largely attributed to the supervision and control mechanisms, which allow the monitoring of sugarcane production dynamics.

It is interesting to note that sugarcane cultivation presents favorable characteristics to be monitored by using remote sensing satellite images [11-18]. Taking this into account, the Brazilian Institute for Space Research (INPE - Instituto Nacional de Pesquisas Espaciais) has been carrying out, since 2003, the Canasat Project (www.dsr.inpe.br/canasat) to annually map the cultivated sugarcane areas in the South-Central region of Brazil using free of cost Landsat type images (www.dgi.inpe.br). The project is supported by the Sugarcane Industry Union (UNICA: União da Indústria de Cana-de-Açúcar), by the Center for Advanced Studies in Applied Economics (CEPEA: Centro de Estudos Avançados em Economia Aplicada) of the Luiz de Queiroz College of Agriculture (ESALQ/USP - Escola Superior de Agricultura Luiz de Queiroz) and by the Sugarcane Technology Center (CTC: Centro de Tecnologia Canavieira).

2. Goal and Objectives

The overarching goal of this study was to use Landsat type images to quantitatively evaluate several aspects related to the sugarcane cultivation dynamic in São Paulo State, Brazil. The specific objectives were:

(1) To map the recent expansion of sugarcane cultivation in São Paulo state with particular emphasis on crop year 2008/09;

(2) To monitor the sugarcane harvest for the classification of fields with and without straw burning practices prior to harvesting;

(3) To identify the land use prior to the additional sugarcane expansion of crop year 2008/09.

3. Materials and Methods

For a better understanding and presentation of this work we first put forward some of the relevant sugarcane characteristics of interest for remote sensing such as: growth cycle, harvest and expansion of cultivation. Next, we describe the method used to carry out the three specific objectives. The whole procedure took place in the state of São Paulo and was based mainly on the 2008/09 crop year.

For the presentation and discussion of results, the state was divided into 15 Administrative Regions (ADRs) defined by the Cartography and Geographic Institute of São Paulo state (IGC: Instituto Geográfico e Cartográfico) for governmental planning purposes. Each ADR is composed of several municipalities within a given geographic region with economic and social similarities (http://www.igc.sp.gov.br/mapasRas.htm).

3.1. Sugarcane Characteristics of Interest for Remote Sensing

A key aspect that promotes the use of remote sensing imagery for applications in sugarcane is the fact that it is a semi-perennial crop that reaches its maximal growth in April, followed by a harvest season that extends until December in the South-Central region. Therefore, the long permanence of the crop in the field increases the chance of acquiring cloud free images, which is fundamental for mapping the cultivated areas, monitoring the harvest and evaluating the land use change dynamic.

3.1.1. Growth Cycle

An understanding of the sugarcane (*Saccharum spp. L.*) growth cycle is important for the correct identification and mapping of the different crop classes in remote sensing images. The sugarcane cycle is semi-perennial and begins with the planting of a stem cutting that grows for about 12 months (year sugarcane) or 18 months (year-and-half sugarcane). After the first harvest, the ratoons are harvested annually for a period of about 5 to 7 years or more. Successive harvests lead to a gradual yield loss until the crop is no longer economically profitable. At this point, the cycle is interrupted, and the area is renovated with the planting of new stem cuttings. Should the ripe sugarcane not be harvested, it will keep on growing to be harvested in the following year.

3.1.2. Harvest

Sugarcane harvesting in the South-Central region of Brazil extends from April to December and is performed in two ways: either manually or mechanically. For manual harvesting, the sugarcane crop is burned prior to cutting the stems in order to eliminate the straw thus making the harvest easier. For mechanical harvesting, burning the straw is unnecessary since the machine cuts off stems and straw leaving the latter scattered on the ground. There is still a third method of harvesting currently used for about 10% of the sugarcane harvested area in São Paulo, which consists of harvesting burned sugarcane fields with less sophisticated machinery. The vast majority of the sugarcane areas in the South-Central region are located on land with slopes ≤ 12%, thereby enabling mechanical harvesting. Interestingly, with mechanical harvesting, the straw residues that remain on the field after the stems are removed look very bright in satellite images, whereas burned areas, where the straw was converted to ashes, appear dark and more similar to bare soil. This aspect is evident even in images acquired several days or even weeks after the harvesting event as Daughtry *et al*. [19] also observed for wheat.

3.1.3. Expansion of Cultivation

The direct land use change caused by the recent and significant expansion of sugarcane [2] can be evaluated from remote sensing images previously recorded for sugarcane plantations [5]. This evaluation allows locating and quantifying the actual amount of pasture land, food production areas, natural vegetation and reforestation, which were converted to sugarcane plantations, and provides relevant information that would otherwise be difficult to obtain.

3.2. Mapping of Sugarcane Cultivated Areas

In the state of São Paulo, the first sugarcane thematic map, within the context of the Canasat Project (www.dsr.inpe.br/canasat), was made for the 2003/04 crop year. This map was obtained by automatic image classification, with a subsequent editing to correct omission and commission errors, using visual/manual interpretation techniques of digital images [18]. The edition was performed by the matrix editing tool of the freeware SPRING software [20], which allows overlying various levels of information simultaneously and interactively, as well as adjusting or correcting the classification result. From the 2004/05 crop year on, we observed that it was more advantageous to perform an annual update of the thematic map only by visual/manual interpretation, based on color, texture, tone, and shape, since correcting omission and commission errors of the automatic image classification was more time consuming. Therefore, the sugarcane classifications to update the thematic map for the subsequent years, including the 2008/09 crop year, were carried out by visual/manual image interpretation at an approximate scale of 1:50,000 using SPRING software.

Multi-temporal and multi-spectral Landsat images from the Thematic Mapper (TM) sensor on board of the Landsat-5 satellite were acquired from January to April of 2008 (crop year 2008/09) to correctly identify the ripe and renovated sugarcane fields in order to precisely forecast the estimated sugarcane area available for sugar and alcohol production at the beginning of the harvest, in April. As an alternative to cloud covered TM images, we used images from High Resolution Imaging Camera (CCD) on board of China-Brazil Earth Resources Satellite-2 and -2B (CBERS-2 and -2B) [21]. For each orbit/point of the TM sensor, we created a database with the least cloud covered images from the dates of interest. All images were registered using first-degree polynomials and interpolation by nearest neighbor, based on the Landsat-7 orthorectified image mosaic obtained from NASA [22]. All registrations were made with a squared mean error of less than 0.5 pixels.

The visual interpretation of the Landsat type images was made by various trained interpreters and later reviewed by a single and more experienced interpreter. Several field works as well as some maps provided by sugarcane plants were used during the image interpretation training process to ensure that the right target was being mapped. Subsequently, the map underwent reclassification of isolated pixels (<1 ha) which remained after the map review. The reclassification was performed using the method proposed in Berka *et al*. [23] which consists in an automatic algorithm based on mode filter and several decision criteria to identify and reclassify the isolated pixels.

3.3. Identification of the Type of Harvest, Either With or Without Straw Burning

Unlike most crops, sugarcane has an extensive harvest calendar, and its monitoring requires the acquisition of images over the entire harvest period, which begins in April and extends through December. The identification of the type of sugarcane harvesting in remote sensing images is performed based on the visual differences between sugarcane harvested areas either with or without the burning practice. Areas where the harvest was processed by straw burning have dark tones on the images due to the presence of ash and bare soil, while areas where the crop was harvested without straw burning appear bright due to the presence of residue composed mainly of dry leaves. The visual image interpretation was performed in two steps: (i) images were evaluated in chronological order by several interpreters, and identified harvested fields were classified according to the harvest type, with or without burning and; (ii) the classification was reviewed by a single experienced interpreter to ensure interpretation uniformity.

A slope digital map, generated from Shuttle Radar Topography Mission (SRTM) images resampled to 30 m pixel size according to the methodology described by Valeriano *et al*. [24], was used to identify sugarcane mechanizable (≤12% slope) and non-mechanizable (>12% slope) areas. The intersection between harvest and slope maps allowed determining the harvest type by slope class which is relevant information for the Agro-environmental Protocol that establishes different deadlines to cease straw burning practice according to terrain slope. Sugarcane fields, in non-mechanizable areas, have a more flexible calendar because eventually they will have to be converted to another land use, unless they are manually harvested, without straw burning, which is not practical.

3.4. Mapping of Land Use Prior to the Sugarcane Cultivation

The sugarcane expansion fields, mapped for the 2008/09 crop year, were selected to identify the land use cover prior to its cultivation. For this purpose, Landsat-5 images from at least two different dates, acquired during the rainy and dry seasons of 2006, were used to identify the land use prior to the sugarcane plantations in 2007 which became available for harvest in the 2008/09 crop year. This identification was performed by visual interpretation techniques. Five land use cover classes were defined according to Nassar *et al*. [5]: Agriculture, Pasture, Reforestation, Forest (natural vegetation) and Citrus.

4. Results and Discussion

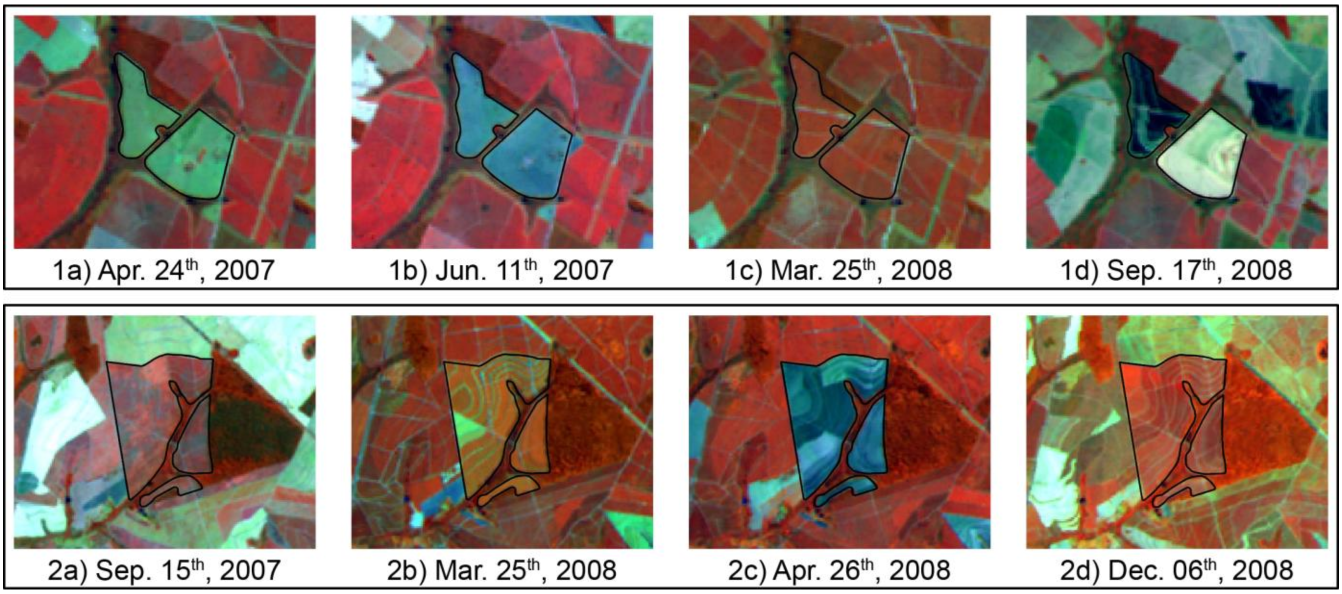
4.1. Sugarcane Identification

Images from January to February, together with images from March to April, provided the best combination to map the spatial distribution of sugarcane cultivation in the state of São Paulo, which consisted in identifying not only the new cultivated sugarcane fields but also the renovated fields, with year-and-half sugarcane plants, using crop rotation. Images from January to February were particularly favorable to identify the renovated fields once they are usually rotated with summer crops such as soybean or peanut that are quite different from sugarcane and can be easily identified on these images. Images from March to April were favorable to identify the new cultivated sugarcane fields; although they could also be well identified on images from January to February. However, for this period some confusion with corn crop was observed, but this was eliminated with the March to April images when the corn crop senesced and contrasted with the well developed sugarcane fields. Images from the January to February period presented more clouds than images from the March to April period. It was not always possible to acquire cloud free images over the entire state in both periods, but in at least one of them all the land, within the sugarcane production regions, could be observed.

Figure 2 presents two sequences of multispectral [4(R)5(G)3(B)] and multi-temporal Landsat-5 images to illustrate typical examples of sugarcane identification based on its visual appearance. Figure 2.1 illustrates the conversion of two highlighted pasture fields (green in Figure 2.1a) to bare soil (blue in Figure 2.1b) and then to ripe sugarcane (red in Figure 2.1c). Eventually, both fields were harvested: one with the practice of straw burning (dark blue in Figure 2.1d) and the other without (almost white in Figure 2.1d). Figure 2.2 illustrates a temporal sequence of three highlighted sugarcane fields that were renovated with one year-and-half sugarcane plants. Figure 2.2a shows old and less productive sugarcane fields with several spots of bare soil before their last harvest in the 2007/08 crop year. In Figure 2.2b it can be observed that these fields were rotated with a summer crop that was seeded at the beginning of the rain season in September/October. Later, in Figure 2.2c, the fields appear as bare soil or as recently planted sugarcane as shown in Figure 2.2d where the renovated and high productive sugarcane fields appear well developed and will be available for harvest in the 2009/10 crop year. It is interesting to note that these renovated sugarcane fields, with crop rotation, skipped one harvest year; therefore, it was important to identify them since they were subtracted from the sugarcane area available for harvest in the 2008/09 crop year. For those fields renovated without crop rotation, the sugarcane was planted at the beginning of the rain season and, therefore, they were available for harvest in the 2008/09 crop year. This type of renovation can hardly be identified by remote sensing images; however, this is not a concern since the yearly sugarcane harvest was not interrupted. In summary, Figures 2.1 and 2.2 illustrate the basic procedure of the annual update of the thematic map which consists in both including new sugarcane fields and excluding renovated ones, with crop rotation, that were not harvested in the 2008/09 crop year.

The correct identification and mapping of the entire cultivated sugarcane area for a large region such as São Paulo state is certainly not a trivial activity and there is not a unique recipe that can be used for different regions and crop years. There are a great number of variables that make the sugarcane fields appear in various manners and their identification is often not evident requiring field work and image interpretation experience to accurately map the sugarcane. The 2008/09 crop year was the sixth consecutive year in which our group performed the sugarcane mapping in São Paulo state making the results available on the Internet. The figures from official institutions, responsible for agricultural statistics based on conventional methods, differ to some extent from our figures. However, we are confident that our figures are quite close to reality and that the precision of our area estimation is much more related to the spatial resolution of the Landsat type images and to the scale (1:50,000) in which interpretation was performed than to thematic omission and commission errors. We are currently working to provide map accuracy based on a scientific method.

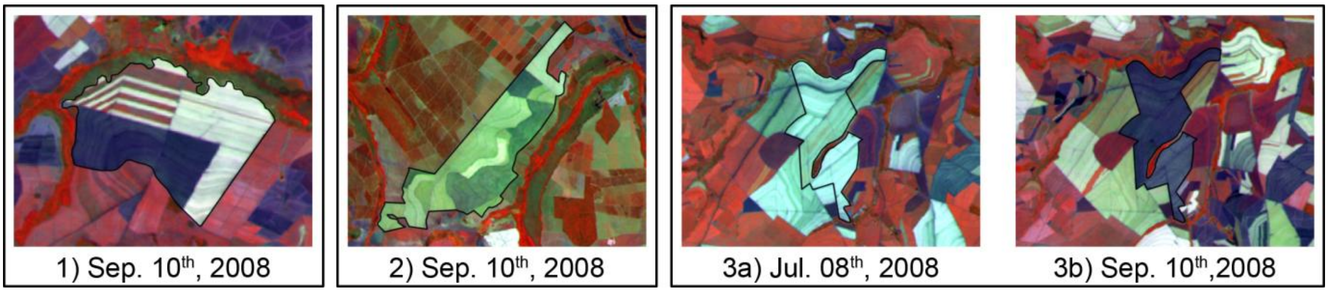
Figure 2. Multispectral [4(R)5(G)3(B)] and multi-temporal Landsat-5 images illustrating the basic procedure to identify new sugarcane fields (**1a**–**1d**) and renovated sugarcane fields with crop rotation (**2a**–**2d**).



4.2. Sugarcane Harvest Type

A considerable number of cloud-free or partially cloud-free Landsat type images were acquired over the entire harvest season, from April to December of 2008. This allowed precisely classifying the sugarcane fields harvested with and without straw burning practices in all sugarcane production regions of São Paulo state. It was important to acquire images relatively soon after the harvest event, otherwise the scar of the harvest type became less evident in the images. Rain events and crop management between harvest and image acquisition date were major factors that influenced the correct identification of the harvest type [12]. For example, straw ridging to facilitate ratoon regrowth and/or application of vinasse for soil enrichment can make the identification of the harvest type in the images much more difficult. However, when the harvest event occurred close to the images acquisition date, as illustrated in Figure 3.1, the harvest type was more than evident. Actually, if the spatial resolution of this image had been high enough, one could even see the machine harvesting this unburned sugarcane field, where the harvested part appears almost white in the image due to the straw carpet that remains after harvesting, while the unharvested sugarcane strips appear in red color. Figure 3.2 illustrates a sugarcane field that was also harvested without burning practices but its scar is no longer evident due to different agricultural practices and/or climatic conditions that occurred between harvest and image acquisition date. Another example given in Figure 3.3a shows a harvested field without straw burning. However, if this field could be observed only with the image presented in Figure 3.3b, a great part of it would have been classified as being harvested with straw burning due to its dark appearance in response to some agricultural practices that removed the straw from the field. Hence, the time elapsed between harvesting and image acquisition may influence the accuracy of the harvest type classification.

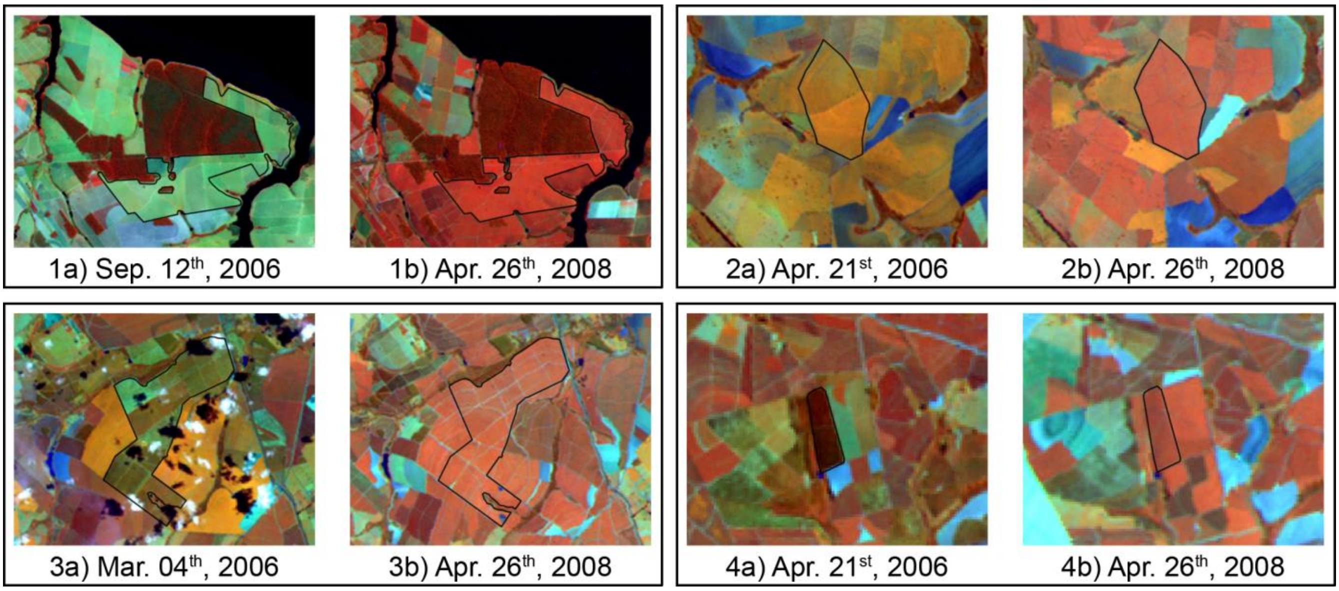
Figure 3. Examples of evident sugarcane fields harvested without straw burning that appear quite bright (**3.1** and **3.3a**) and examples of not so evident sugarcane fields harvested without straw burning that appear in greenish color (**3.2** and **3.3b**). Dark blue fields that appear in almost all figures are typical of sugarcane harvested with straw burning.



4.3. Land Use Change

To illustrate the identification of land use prior to sugarcane cultivation, some examples are presented in Figures 4.1 to 4.4. In Figure 4.1a a typical pasture land can be observed in the image from September 12, 2006. Later, on April 26, 2008 (Figure 4.1b) a well developed sugarcane field replaced this pasture land. In Figure 4.2a a highlighted agricultural crop field on the image from April 21, 2006 was converted to sugarcane as it can be observed in the image from April 26, 2008 (Figure 4.2b). Figure 4.3a shows an image from March 04, 2006, highlighting a citrus field converted to sugarcane, as shown in the image from April 26, 2008 (Figure 4.3b). Finally, Figure 4.4a highlights a field of reforestation in the image of April 21, 2006 that was converted to sugarcane as illustrated in Figure 4.4b with the image from April 26, 2008.

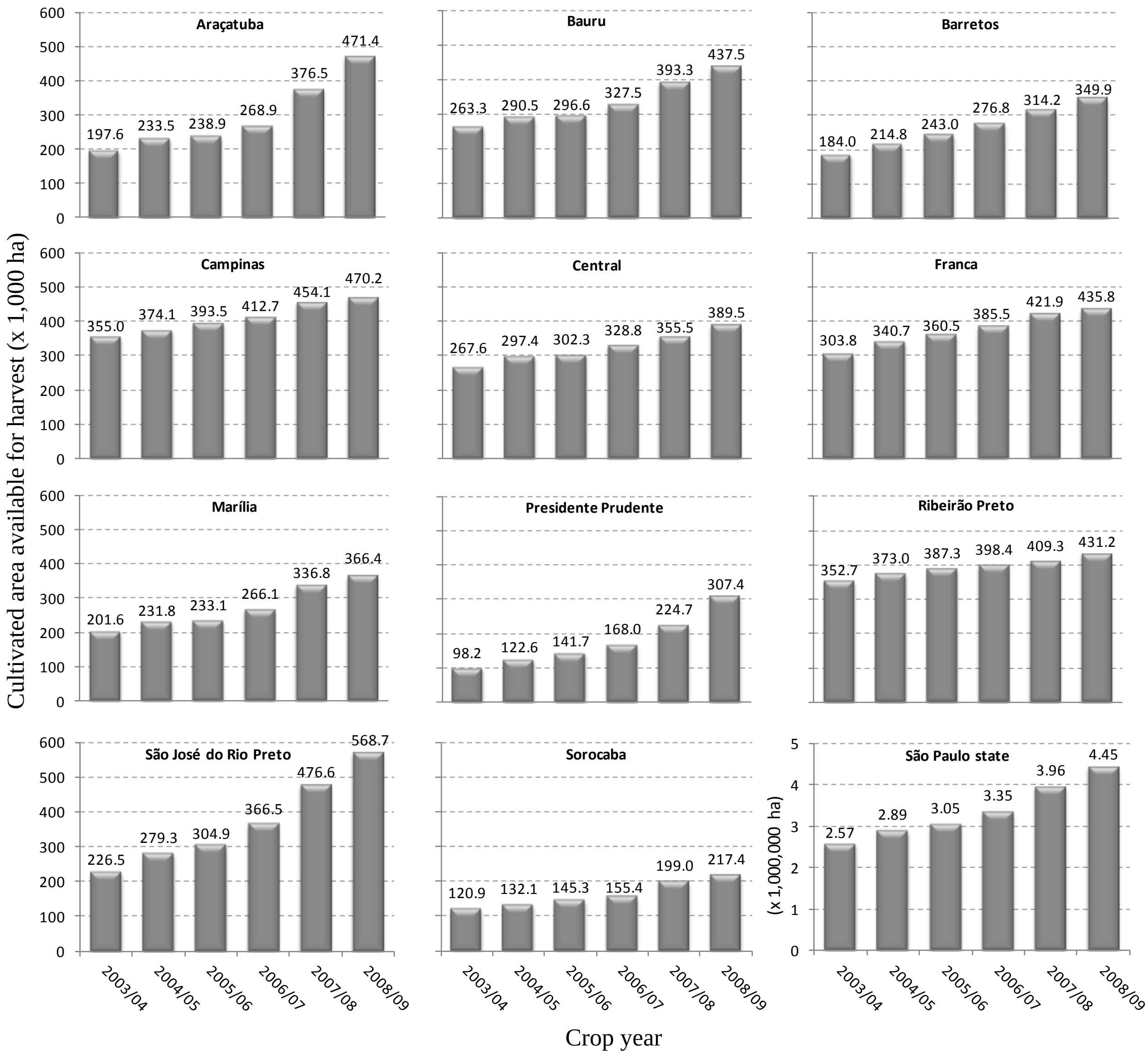
Figure 4. Examples of four different land use conversion: from pasture to sugarcane (**4.1a**, **4.1b**); from agricultural crop to sugarcane (**4.2a**, **4.2b**); from citrus to sugarcane (**4.3a**, **4.3b**); and from reforestation to sugarcane (**4.4a**, **4.4b**).



4.4. Spatial Distribution

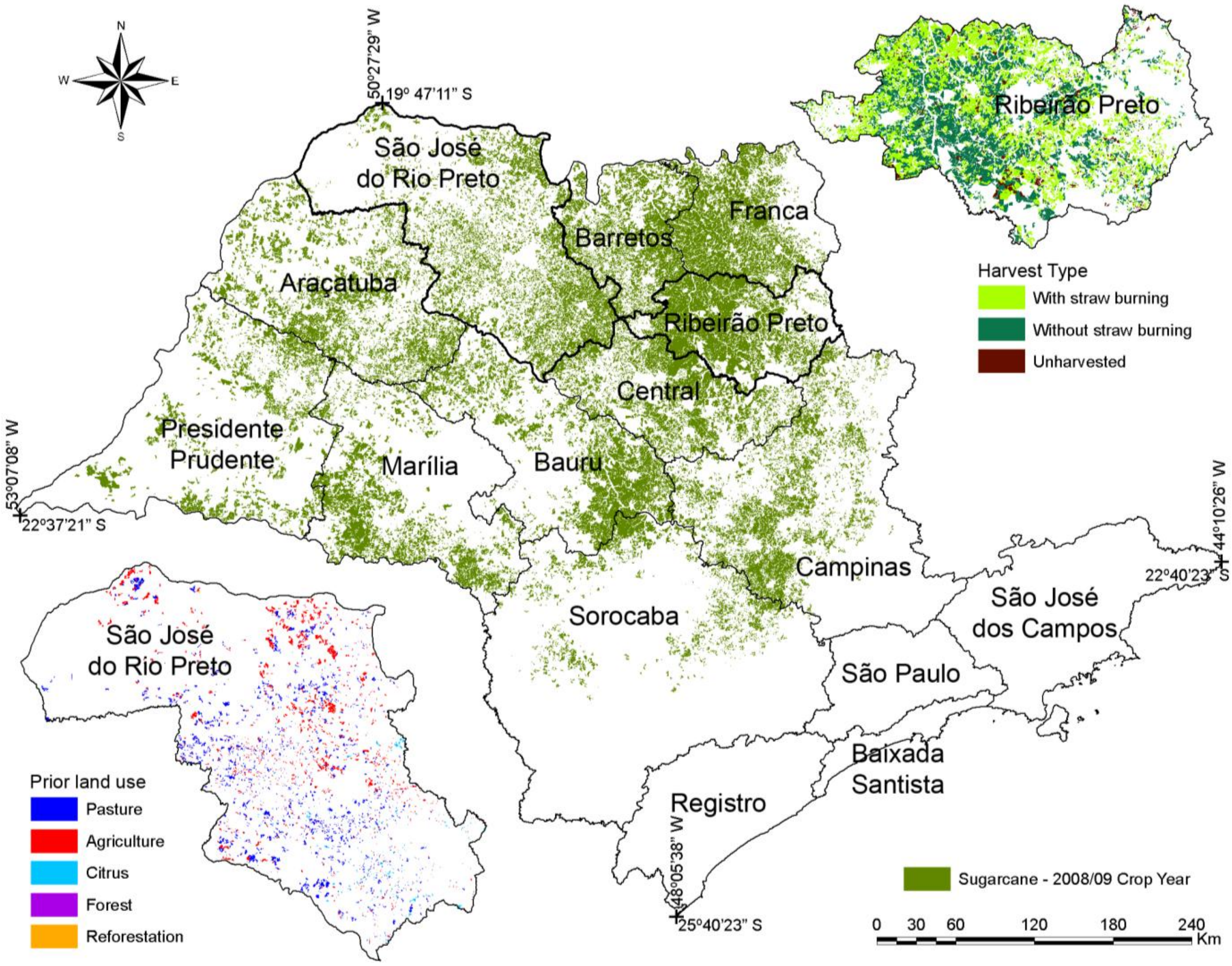
A summary of the cultivated sugarcane area evaluated from Landsat type images for each Administrative Region of São Paulo state from crop year 2003/04 to 2008/09 is presented in Figure 5. Sugarcane production became a significant incentive in 2002 with the announcement of the flex fuel vehicles by the Brazilian automobile industry. São Paulo state provided the fastest response to supply the rapid increase in ethanol demand. A major increase in sugarcane production was observed not only in traditional sugarcane and annual crop producing regions such as Ribeirão Preto, Central, Franca and Barretos, but also in regions that are more devoted to cattle-raising in the western part of São Paulo state such as São José do Rio Preto, Araçatuba and Presidente Prudente.

Figure 5. Cultivated sugarcane area available in thousands of ha from crop years 2003/04 to 2008/08 for each Administrative Regions (ADRs) and for São Paulo state.



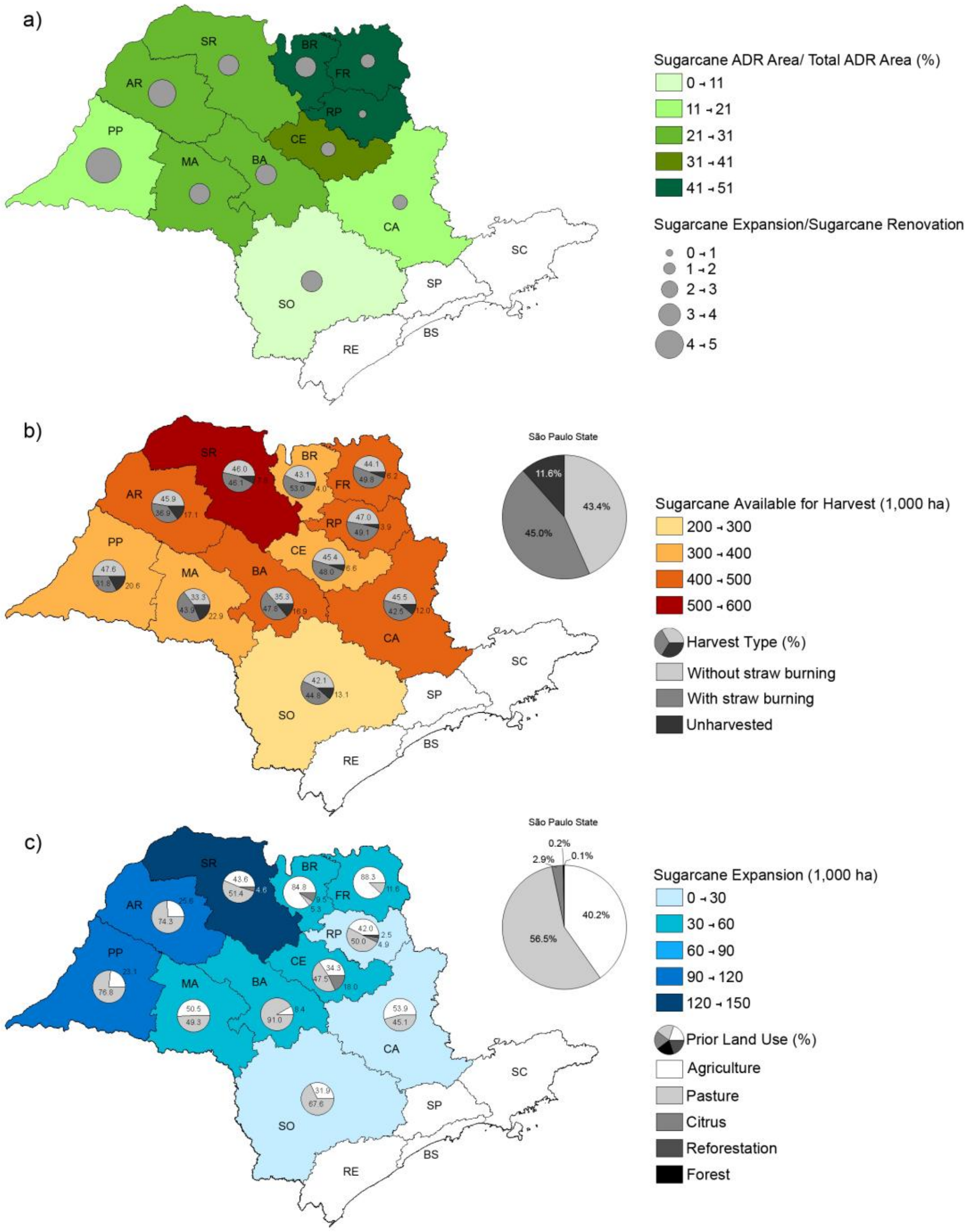
The distribution of the mapped sugarcane cultivated areas in São Paulo state, for the 2008/09 crop year, by Administrative Regions (ADRs), is illustrated in Figure 6. Only four ADRs located in the southeast of the state (São José dos Campos, São Paulo, Baixada Santista and Registro) do not produce significant sugarcane due to relatively unfavorable environmental conditions [25]. The total cultivated area with sugarcane in the state of São Paulo in the 2008/09 crop year was 4.87 million ha (19.6% of São Paulo state territory), of which 4.45 million ha were available for harvesting at the beginning of the harvest season in April of 2008 and 428 thousand ha were under renovation with year-and-half sugarcane (Table 1).

Figure 6. Cultivated sugarcane areas by Administrative Regions (ADRs) of São Paulo state for the 2008/09 crop year. The ADR of Ribeirão Preto is detached to exemplify the map of harvest type during the 2008/09 crop year. The ADR of São José do Rio Preto is detached to exemplify the map of prior land use in the expanded sugarcane fields of 2008/09 crop year.



The highest concentration of sugarcane cultivation is located in the north-central part of the state where the ADRs of Ribeirão Preto, Franca and Barretos have their territory occupied by 41 to 51% of sugarcane crop (Figure 7a). Although the ADR of Sorocaba has the lowest concentration of sugarcane cultivation (Figure 7a) as well as the lowest cultivated area among the sugarcane producing ADR (Table 1), its distribution is not homogeneous and concentrated mainly in the northern border (Figure 6). The ADRs of São José do Rio Preto and Araçatuba have not only the largest number of sugarcane cultivated areas but also the largest sugarcane expansion (Table 1). However, their percentages of occupancy are not among the highest, ranging from 21 to 31% (Figure 7a). Considering that these

Figure 7. (a) Percentage classes of cultivated sugarcane area and ratio classes of expansion area to renovation area; (**b)** Classes of available sugarcane area and proportions of: harvested with straw burning, harvested without straw burning and unharvested; (**c)** Classes of sugarcane expansion area and proportions of land use change for: pasture, agriculture, citrus, forest (natural vegetation) and reforestation for the Administrative Regions (ADRs) of Araçatuba (AR), Baixada Santista (BS), Barretos (BR), Bauru (BA), Campinas (CA), Central (CE), Franca (FR), Marília (MA), Presidente Prudente (PP), Registro (RE), Ribeirão Preto (RP), São José do Rio Preto (SR), São José dos Campos (SC), São Paulo (SP) and Sorocaba (SO).



ADRs are quite favorable for sugarcane production and have a considerable amount of pasture land, they are likely to continue the sugarcane expansion during the next years. By analyzing the results presented in Table 1 and Figure 7a, the ADR of Presidente Prudente is the third largest ADR of sugarcane expansion with a relative low percentage of sugarcane cultivation (11 to 21%). The ADR of Presidente Prudente has similar characteristics to the ADRs of São José do Rio Preto and Araçatuba in terms of potential for sugarcane expansion. Therefore, it is also likely that Presidente Prudente will continue to be among the ADRs with the greatest sugarcane expansion in the near future.

Figure 7a illustrates the expansion/renovation ratio of sugarcane area showing that the ADRs of São José do Rio Preto, Araçatuba and Presidente Prudente have relatively new areas of sugarcane with much more expansion than renovation. Conversely, the traditional sugarcane cultivation region of Ribeirão Preto has three times more renovation than expansion (Table 1 and Figure 7a). Other traditional sugarcane cultivation ADRs are Franca, Central and Campinas where expansion/renovation ratio is close to one but tends to decrease due to the high concentration of sugarcane, less available land for expansion, and continue renovation of old sugarcane fields.

4.5. Harvest Monitoring

Sugarcane harvest monitoring throughout the season of 2008 showed that a total of 3.93 million ha were harvested in the state of São Paulo, representing 88.4% harvesting available areas at the beginning of the season, in April (4.45 million ha; Table 2). The unharvested sugarcane area represented 11.6% (Table 2 and Figure 7b), which, according to UNICA [4], was the largest unharvested sugarcane area reported in recent seasons; especially for the ADRs located in the southwest part of the State. This year´s large amount of unharversted sugarcane was due, in part, to the lower industry crushing capacity in relation to the sugarcane availability, because many of the new industrial units delayed their start or operated below full capacity. Unexpected and excessive rainfall during the harvest season also contributed to the increased amount of unharvested sugarcane [26].

Of the total harvested sugarcane in 2008 (3.93 million ha), 49.1% (1.93 million ha) was done without sugarcane straw burning practices, and 50.9% (2.00 million ha) was with the straw burning practice prior to harvest (Table 2) which indicates that burning practices are still widely used in São Paulo state. However, Aguiar *et al*. [6] reported, also for the state of São Paulo, that during the 2006 season 3.24 million ha were harvested and that 33.5% (1.09 million ha) were harvested without straw burning and 66.5% (2.15 million ha) with straw burning. Comparing the results it can be concluded that from 2006 to 2008 the unburned harvested area increased by 0.84 million ha and the burned area decreased by 0.15 million ha. This is quite a positive result for the Agro-environmental Protocol that intends to gradually cease the practice of straw burning by 2014 in mechanizable areas.

Another positive aspect that will facilitate compliance with the Agro-environmental Protocol is that in 2008 only 3.2% of the sugarcane available for harvest was located in areas with slope >12% and that 96.8% was located in areas with slopes ≤12% (Table 1). Furthermore, all of the ADRs have at least 92.1% of their cultivated sugarcane in areas with slope ≤12% (Table 1). During the 2008 harvest season, 1.92 million ha were harvested with straw burning practice in areas with slope ≤12% and only 84.5 thousand ha were harvested with straw burning in areas with slope >12% (Table 2). Therefore, the slope factor is not limiting the harvest mechanization.

Table 1. Information on sugarcane cultivated area for the Administrative Regions (ADRs) of São Paulo state, crop year 2008/09: (1) cultivated area available for harvest; (2) cultivated area by terrain slope; (3) cultivated area under renovation; (4) total cultivated area; and (5) direct land use change for cultivated area of sugarcane expansion.

ADR	[1] Available for harvest (ha)				[2] Total available sugarcane by slope [e]				[3] Under renovation (ha)	[4] Total cultivated (ha) [d+f]	[5] Direct land use change for expansion (ha)				
	Ratoon [a]	Renovated [b]	Expansion [c]	Total [d]					[f]		Agriculture	Pasture	Citrus	Forest	Reforest
					≤12% (ha)	(%)	>12% (ha)	(%)							
Araçatuba	332,489	20,855	118,020	471,364	470,182	99.7	1,182	0.3	41,239	512,603	30,196	87,651	59	93	21
Baixada Santista	0	0	0	0	0	0.0	0	0.0	0	0	0	0	0	0	0
Barretos	277,358	17,966	54,592	349,916	347,938	99.4	1,978	0.6	35,675	385,591	46,284	2,880	5,161	204	63
Bauru	350,856	28,176	58,462	437,494	422,780	96.6	14,714	3.4	36,657	474,151	4,902	53,195	202	98	64
Campinas	410,604	33,772	25,831	470,207	433,055	92.1	37,152	7.9	40,816	511,023	13,932	11,655	87	71	85
Central	313,764	37,511	38,216	389,491	370,784	95.2	18,707	4.8	42,821	432,312	13,120	18,149	6,874	65	8
Franca	369,067	27,182	39,531	435,780	416,938	95.7	18,842	4.3	53,281	489,061	34,912	4,577	0	34	8
Marília	291,695	21,029	53,661	366,385	361,085	98.6	5,300	1.4	39,494	405,879	27,114	26,443	0	104	0
Presidente Prudente	199,906	10,154	97,344	307,404	304,893	99.2	2,511	0.8	19,683	327,087	22,514	74,754	18	45	13
Registro	0	0	0	0	0	0,0	0	0.0	0	0	0	0	0	0	0
Ribeirão Preto	370,269	46,637	14,282	431,188	410,170	95.1	21,018	4.9	40,252	471,440	6,005	7,148	707	61	361
São José do Rio Preto	409,426	25,120	134,131	568,677	565,754	99.5	2,923	0.5	63,362	632,039	58,416	68,946	6,104	483	182
São José dos Campos	0	0	0	0	0	0,0	0	0.0	0	0	0	0	0	0	0
São Paulo	0	0	0	0	0	0,0	0	0.0	0	0	0	0	0	0	0
Sorocaba	180,977	8,590	27,804	217,371	200,292	92.1	17,079	7.9	15,383	232,754	8,877	18,783	50	1	94
State of São Paulo	**3,506,411**	**276,992**	**661,874**	**4,445,277**	**4,303,871**	**96.8**	**141,406**	**3.2**	**428,663**	**4,873,940**	**266,272**	**374,180**	**19,262**	**1,260**	**900**

a = ratoon sugarcane, or regrowth after each harvest; b = renovated sugarcane with year-and-half plant in previous crop year; c = expansion sugarcane to be harvested for the first time; d = total available sugarcane for harvest (a + b + c); e = total available sugarcane for harvest by slope; f = sugarcane area under renovation with year-and-half plant (not yet available for harvest).

Table 2. Information on harvested and unharvested sugarcane area for the Administrative Regions (ADRs) of São Paulo state, crop year 2008/09: 1) total available sugarcane area: (a) harvested with straw burning, (b) harvested without straw burning, and c) unharvested; (2) available sugarcane area with slope ≤12%: (d) harvested with straw burning, (e) harvested without straw burning, and (f) unharvested; (3) available sugarcane area with slope ≤12%: (g) harvested without straw burning, (h) harvested with straw burning, and (i) unharvested.

ADR	[1] Total available sugarcane area						[2] Available sugarcane area with slope ≤12%						[3] Available sugarcane area with slope >12%					
	Harvested without straw burning		Harvested with straw burning		Unharvested		Harvested without straw burning		Harvested with straw burning		Unharvested		Harvested without straw burning		Harvested with straw burning		Unharvested	
	(ha) [a]	(%) [a/(a+b]	(ha) [b]	(%) [b/(a+b]	(ha) [c]	(%) [c/(a+b+c]	(ha) [d]	(%) [d/(d+e)]	(ha) [e]	(%) [e/(d+e)]	(ha) [f]	(%) [f/(d+e+f)]	(ha) [g]	(%) [g/(g+h)]	(ha) [h]	(%) [h/(g+h)]	(ha) [i]	(%) [h/(g+h+i)]
Araçatuba	216,530	55.4	174,042	44.6	80,791	17.1	216,060	55.5	173,601	44.5	80,521	17.1	471	51.6	441	48.4	270	22.9
Baixada Santista	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Barretos	150,661	44.8	185,362	55.2	13,892	4.0	150,137	44.9	184,019	55.1	13,782	4.0	524	28.1	1,343	71.9	111	5.6
Bauru	154,459	42.5	208,935	57.5	74,100	16.9	151,425	43.1	199,847	56.9	71,508	16.9	3,034	25.0	9,088	75.0	2,592	17.6
Campinas	213,945	51.7	199,747	48.3	56,514	12.0	200,575	52.4	182,209	47.6	50,271	11.6	13,370	43.3	17,539	56.7	6,244	16.8
Central	176,861	48.6	187,026	51.4	25,604	6.6	173,833	50.0	173,504	50.0	23,447	6.3	3,028	18.3	13,522	81.7	2,157	11.5
Franca	192,037	47.0	216,902	53.0	26,841	6.2	188,636	48.1	203,771	51.9	24,531	5.8	3,400	20.6	13,131	79.4	2,310	12.2
Marília	121,851	43.1	160,723	56.9	83,811	22.9	120,691	43.3	157,938	56.7	82,455	22.8	1,160	29.4	2,785	70.6	1,356	25.6
Presidente Prudente	146,364	59.9	97,806	40.1	63,234	20.6	145,498	60.0	96,899	40.0	62,497	20.5	866	48.9	907	51.1	738	29.4
Registro	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Ribeirão Preto	202,478	48.9	211,841	51.1	16,869	3.9	197,847	50.1	196,934	49.9	15,389	3.8	4,630	23.7	14,907	76.3	1,480	7.0
São José do Rio Preto	261,862	49.9	262,421	50.1	44,394	7.8	260,896	50.0	260,780	50.0	44,079	7.8	966	37.1	1,642	62.9	315	10.8
São José dos Campos	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
São Paulo	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
Sorocaba	91,513	48.4	97,408	51.6	28,450	13.1	86,248	49.4	88,217	50.6	25,827	12.9	5,265	36.4	9,192	63.6	2,622	15.4
State of São Paulo	**1,928,560**	**49.1**	**2,002,215**	**50.9**	**514,502**	**11.6**	**1,891,845**	**49.7**	**1,917,719**	**50.3**	**494,307**	**11.5**	**36,715**	**30.3**	**84,496**	**69.7**	**20,195**	**14.3**

According to Lara *et al*. [27], about 20 metric tons of dry sugarcane material is burned per ha, contributing with about 0.48 Tg of carbon per year to global emissions. According to Soares *et al*. [28], sugarcane harvest without straw burning reduces the emission of greenhouse gases for a total of 1.72 metric tons of carbon dioxide (CO_2)-equivalent per ha which corresponds to almost 80% of the total greenhouse gases emission of the harvest process performed with straw burning. Thus, assuming that the mechanizable areas will have achieved the Agro-environmental Protocol by 2014 and that new sugarcane planted areas will be harvested without burning, then 3.30 million metric tons of CO_2 equivalent per year will no longer be released into the atmosphere. Considering that 2.00 million ha were mechanically harvested in 2008, without straw burning (Table 2), it can be estimated that about 3.32 million metric tons of CO_2 equivalent were saved from being released into the atmosphere due to the harvest without straw burning.

According to Table 2, the ADRs that harvested the most without burning, in relation to its total area, were Presidente Prudente (59.9%-146,364 ha) and Araçatuba (55.4%-216,530 ha). This can be partially justified due to the fact that these ADRs have more than 99% of its cultivated sugarcane in mechanizable areas (Table 1). The ADRs of Bauru and Marília presented the highest percentages of burned sugarcane area although slope cannot be considered a limiting factor for mechanical harvest in these ADRs since more than 96% of cultivated sugarcane is located in slopes ≤ 12%. A major reason responsible for the high percentages of mechanical harvest without straw burning in some regions is that the latest investments in the sector must consider environmental regulations such as the Agro-environmental Protocol. In more traditional regions the producers have to adapt and this is a gradual process. Remote sensing images that can monitor the harvest process are a key element to evaluate the effectiveness of the measures to reduce and eventually cease the straw burning harvest procedure.

The spatially distributed information on the sugarcane harvest type (see ADR of Ribeirão Preto in Figure 6) is an important data source for studies on the effect of sugarcane straw burning on respiratory illnesses [29,30]. Currently, such studies have used data from fire outbreaks provided by INPE (http://sigma.cptec.inpe.br/queimadas). However, these data are general and do not specify which land use cover the outbreaks come from nor their precise geographical position.

4.6. Direct Land Use Change

Table 1 and Figure 7c show the results of direct land use change in response to sugarcane planted in 2007 and available for harvest for the 2008/09 crop season. For the entire state, 56.5% of the expanded sugarcane area occurred over pasture land and 40.2% over agricultural land with annual summer crops. Other classes of land use (citrus, forest or natural vegetation, and reforestation) prior to sugarcane represented altogether 3.24%. In Figure 7c it can be noticed that the ADRs located towards the north-western part of the state had the most significant sugarcane expansion with most of it over pasture land, while the ADRs located towards the north-eastern part of the state had less sugarcane expansion with a significant part of it over agricultural land. However, the figures for sugarcane expansion over agricultural land should be analyzed carefully since the conversion of pasture land to sugarcane is often a process that takes more than a year. It is often observed that a pasture field is converted to an annual summer crop before sugarcane is planted [13]. In this case, according to the method used in this work, the sugarcane expansion is computed as being over agricultural land when it is actually over a pasture land. Further studies using a wider range of multi-temporal images should be carried out to address the process of land conversion under a broader time frame.

The ADRs of Araçatuba, Presidente Prudente and São José do Rio Preto presented the largest sugarcane expansion and also the largest conversion of pasture land to sugarcane (Table 1 and Figure 7c). Together they accounted for 62% of the pasture land converted to sugarcane in the state of São Paulo. In these regions extensive livestock used to be the adopted farming system. However, many farmers have changed this farming system to a more intensive livestock making more land available for sugarcane production [31]. In the ADRs of Araçatuba and Presidente Prudente the sugarcane expansion on pasture land was 74.3% and 76.8%, respectively (Figure 7c).

The ADRs of São José do Rio Preto, Barretos and Franca had the largest amount of agricultural land replaced by sugarcane (Table 1), accounting for 52% of total agricultural land converted to sugarcane in the state. Barretos and Franca had, respectively, 84.8 and 88.3% of their sugarcane expansion areas over agricultural land (Figure 7c). These two ADRs have a long history on agriculture and livestock activities which are being intensified with the expansion of sugarcane cultivation. The ADR of São José do Rio Preto is mainly known as a major livestock region but also has significant production of coffee, cotton, corn and fruit [32]. Significant sugarcane expansion has been observed in this region over recent years (http://www.dsr.inpe.br/canasat) and in 2008 it presented the largest sugarcane expansion area.

5. Conclusions

The Landsat type images were highly suitable for mapping and evaluating the rapid expansion of sugarcane areas in São Paulo state from 2003 to 2008 when an additional area of 1.88 million ha of sugarcane was cultivated to meet the increaseing demand of ethanol to supply fuel to flex automobiles.

Sugarcane harvest monitoring using remote sensing images proved to be a viable procedure to identify sugarcane harvested either with or without straw burning practices showing that currently 50% of the sugarcane area was harvested without straw burning indicating that the Agro-environmental Protocol has been efficient at reducing sugarcane straw burning.

Finally, remote sensing images were essential in assessing the direct impact on land use change due to the large expansion of sugarcane cultivation showing that sugarcane expands almost exclusively over pasture land and annual agricultural crops with almost 50% of expansion each.

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References and Notes

1. Moreira, J.R.; Goldemberg, J. The alcohol program. *Energ. Policy* **1999**, *27*, 229-245.

2. Nass, L.L.; Pereira, P.A.A.; Ellis, D. Biofuels in Brazil: an overview. *Crop Sci.* **2007**, *47*, 2228-2237.
3. FAOSTAT. Food and Agriculture Organization of the United Nations. Available online: http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567# ancor (accessed on 14 May 2009).
4. Dados e Cotações—Estatísticas. UNICA (União da Indústria de Cana-de-açúcar). Avaliable online: http://www.unica.com.br/dadosCotacao/estatistica/ (accessed on 15 November 2009).
5. Nassar, A.M.; Rudorff, B.F.T.; Antoniazzi, L.B.; Aguiar, D.A.; Bacchi, M.R.P.; Adami, M. Prospects of the sugarcane expansion in Brazil: impacts on direct and indirect land use changes. In *Sugarcane Ethanol: Contributions to Climate Change Mitigation and the Environment*, Zuurbier, P., van de Vooren, J., Eds.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2008; pp. 63-93.
6. Aguiar, D.A.; Rudorff, B.F.T.; Adami, M.; Shimabukuro, Y.E. Imagens de sensoriamento remoto no monitoramento da colheita da cana-de-açúcar. *Revista de Engenharia Agrícola* **2009**, *29*, 440-451. DOI: 10.1590/S0100-69162009000300011.
7. Goldemberg, J. Ethanol for a sustainable energy future. *Science* **2007**, *315*, 808-810.
8. Goldemberg, J.; Coelho, S.T.; Guardabassi, P. The sustainability of ethanol production from sugarcane. *Energ. Policy* **2008**, *36*, 2086-2097.
9. Smeets, E.; Junginger, M.; Faaij, A.; Walter, A.; Dolzan, P.; Turkenburg, W. The sustainability of Brazilian ethanol—an assessment of the possibilities of certified production. *Biomass Bioenerg.* **2008**, *32*, 781-813.
10. Amaral, W.A.N.; Marinho, J.P.; Tarasantchi, R.; Beber, A.; Giuliani, E. Environmental sustainability of sugarcane ethanol in Brazil. In *Sugarcane Ethanol: Contributions to Climate Change Mitigation and the Environment*; Zuurbier, P., van de Vooren, J., Eds.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2008; pp. 113-138.
11. El Hajj, M.; Bégué, A.; Guillaume, S.; Martiné, J.F. Integrating SPOT-5 time series, crop growth modeling and expert knowledge for monitoring agricultural practices—The case of sugarcane harvest on Reunion Island. *Remote Sens. Environ.* **2008**, *113*, 2052-2061.
12. Baghdadi, N.; Boyer, N.; Todoroff, P.; El Hajj, M.; Bégué, A. Potential of SAR sensors TerraSAR-X, ASAR/ENVISAT and PALSAR/ALOS for monitoring sugarcane crops on Reunion Island. *Remote Sens. Environ.* **2009**, *113*, 1724-1738.
13. Rudorff, B.F.T.; Adami, M.; Aguiar, D.A.; Gusso, A.; Silva, W.F.; Freitas, R.M. Temporal series of EVI/MODIS to identify land converted to sugarcane. *In Proceedings of IEEE International Geoscience and Remote Sensing Symposium*, Cape Town, South Africa, 2009.
14. Abdell-Rahman, E.M.; Ahmed, F.B. The application of remote sensing techniques to sugarcane (Saccharum spp. hybrid) production: a review of the literature. *Int. J. Remote Sens.* **2008**, *29*, 3753-3767.
15. Fortes, C.; Demattê, J.A.M. Discrimination of sugarcane varieties using Landsat 7 ETM+ spectral data. *Int. J. Remote Sens.* **2006**, *27*, 1395-1412.
16. Xavier, A.C.; Rudorff, B.F.T.; Shimabukuru, Y.E.; Berka, L.M.S.; Moreira, M.A. Multi-temporal analysis of MODIS data to classify sugarcane crop. *Int. J. Remote Sens.* **2006**, *27*, 755-768.
17. Galvão, L.S.; Formaggio, A.R.; Tisot, D.A. The influence of spectral resolution on discriminating Brazilian sugarcane varieties. *Int. J. Remote Sens.* **2006**, *27*, 769-777.

18. Rudorff, B.F.T.; Berka, L.M.S.; Moreira, M.A.; Duarte, V.; Xavier, A.C.; Rosa, V.G.C.; Shimabukuro, Y.E. Imagens de satélite no mapeamento e estimativa de área de cana-de-açúcar em São Paulo: ano-safra 2003/04. *Agricultura em São Paulo* **2005**, *52*, 21-39.
19. Daughtry, C.S.; Serbin, G.; Reeves, J., III; Doraiswamy, P.; Hunt, E.R., Jr. Spectral Reflectance of Wheat Residue during Decomposition and Remotely Sensed Estimates of Residue Cover. *Remote Sens.* **2010**, *2*, 416-431.
20. Câmara, G.; Souza, R.C.M.; Freitas, U.M.; Garrido, J.; Ii, F.M. SPRING: Integrating remote sensing and GIS by object oriented data modeling. *Comput. Graph.* **1996**, *15*, 13-22.
21. Epiphanio, J.C.N.; Soares, J.V.; Ferreira, H.S.; Câmara, G. CBERS: the Chinese-Brazilian Earth Resources Satellite programme. In *The Full Picture*, GEO—Group on Earth Observations, Tudor Rose: Geneva, Switzerland, 2007, pp. 116-117. Available online: http://www.earthobservations.org/documents/the_full_picture.pdf (accessed 24 March 2010).
22. *Orthorectified Landsat Enhanced Thematic Mapper (ETM+) Compressed Mosaics*. NASA: Washington, DC, USA, 2004. Available online: https://zulu.ssc.nasa.gov/mrsid/ (accessed on 13 March 2007).
23. Berka, L.M.S.; Rudorff, B.F.T.; Freitas, R.M. Reclassificação controlada de pixels isolados em mapas de cana-de-açúcar. In *Proceedings of Anais 12 Simpósio Brasileiro de Sensoriamento Remoto*, Goiânia, Brazil, 2005; pp. 33-40. Available online: http://marte.dpi.inpe.br/col/ltid.inpe.br/sbsr/2004/11.19.19.37/doc/Berka.pdf (accessed on 24 March 2010).
24. Valeriano, M.M.; Kuplich, TM.; Storino, M.; Amaral, B.D.; Mendes, J.N., Jr.; Lima, D.J. Modeling small watersheds in Brazilian Amazônia with shuttle radar topographic mission-90 m data. *Comput. Geosci.* **2006**, *32*, 1169-1181.
25. Alfonsi, R.R.; Pedro Júnior, M. J.; Brunini,O.; Barbieri, V. Condições climáticas para a cana-de-açúcar. In *Cana-de-açúcar: cultivo e utilização*. Paranhos, S.B., Ed.; Fundação Cargill: Campinas, Brazil, 1987; pp. 42-55.
26. Aguiar, D.A.; Silva, W.F.; Feitosa, F.F.; Gonçalves, G.G.; Rizzi, R.; Rudorff, B.F.T. Análise espacial da colheita da cana-de-açúcar no Estado de São Paulo: a influência da precipitação. In *Proceedings of Anais 13 Simpósio Brasileiro de Sensoriamento Remoto*, Florianópolis, Brazil, 2007; pp. 2231-2238. Available online: http://marte.dpi.inpe.br/col/dpi.inpe.br/sbsr@80/2006/11.15.15.48/doc/2231-2238.pdf (accessed on 11 January 2010).
27. Lara, L.L.; Artaxo, P.; Martinelli, L.A.; Camargo, P.B.; Victoria, R.L.; Ferraz, E.S.B. Properties of aerosols from sugar-cane burning emissions in Southeastern Brazil. *Atmos. Environ.* **2005**, *39*, 4627-4637.
28. Soares, L.H.B.; Alves, B.J.R.; Urquiaga, S.; Boddey, R.M. Brazilian ethanol and the mitigation of greenhouse gases emission. *Revista Brasileira de Bioenergia*. **2009**, *6*, 48-53. Available online: http://cenbio.iee.usp.br/download/revista/RBB6.pdf (accessed on 24 March 2010).
29. Cançado, J.E.D; Saldiva, P.H.N.; Pereira, L.A.A.; Lara, L.B.L.S.; Artaxo, P.; Martinelli, L.A.; Arbex, M.A.; Zanobetti, A.; Braga, A.L.F. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. *Environ. Health Perspect.* **2006**, *114*, 725-729.
30. Uriarte, M.; Yackulic, C.B.; Cooper, T.; Flynn, D.; Cortes, M.; Crk, T.; Cullman, G.; McGinty, M.; Sircely. J. Expansion of sugarcane production in São Paulo, Brazil: implications for fire occurrence and respiratory health. *Agr. Ecosyst. Environ.* **2009**, *132*, 48-56.

31. *Projeto LUPA 2007/08: censo agropecuário do Estado de São Paulo*. Torres, A.J., Pino, F.A., Francisco, V.F.S., Ângelo, J.A., Maciel, E.L.F., Drugowich, M.I., Interliche, P.H., Piedade, J.A., Sousa, A.C., Lorena Neto, B., Caser, D.V., Eds.; IEA, CATI, SAA: São Paulo, Brasil, 2009; p. 381.
32 *Região Administrativa de São José do Rio Preto*. SEADE (Fundação Sistema Estadual de Análise de Dados). Available online: http://www.seade.gov.br/produtos/iprs/analises/ RASJRiopreto.pdf (accessed on 29 March 2009).