Economic and environmental impacts in sugarcane production to meet the Brazilian ethanol demands by 2030: the role of Precision Agriculture

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Abstract. *The agreement signed at COP-21 reaffirms the vital compromise of Brazil with sugarcane and ethanol production. To meet the established targets, the ethanol production should be 54 billion liters in 2030. From the agronomic standpoint, two alternatives are possible; increase the planted area and/or agricultural yield. The present study aimed to evaluate the economic and environmental impacts in sugarcane production meeting the established targets in São Paulo state. In this context, were evaluated how the precision agriculture (PA) technologies could help sugarcane production reach the established targets from agreement. Only expanding the area, an increase of 2 million hectares (ha) would be required, suggesting that the expansion should be in other Brazilian states as well. However, scientific results have shown that it is more feasible to increase the agricultural yield. This alternative can reduce 29% of the total production costs. Considering that the average yield should rise from 77.5 Mg ha-1 to 111 Mg ha-1 by 2030, the total production costs will be reduced 29%. The use of PA technologies can contribute significative reducing production cost and increasing agricultural yield. From an environmental point of view, the adoption of PA technologies can reduce around 20% of climate change and fossil depletion compared with current scenario, that will be essential to reach the goals. Manage spatial and temporal variability of crops and soils will allow to maximize the sugarcane production, reducing production costs and environmental impacts through the rational use of inputs.*

Keywords. *sugarcane production, economic assessment, precision agriculture, environmental assessment.*

Introduction

December 12, 2015 was a historic day for the world. More than 195 nations in Paris-France decided to combat global climate changes (COP-21, Paris, France). This agreement provided an international engagement to limit the global temperature increase. One of the focus of the agreement is the low-carbon economy. So, Brazil plays a fundamental key for nations around the world, through the ethanol production; a renewable fuel that can mitigate the climate change. Thus, the production and export of Brazilian ethanol, which is increasing every year (OECD-FAO Agricultural Outlook 2015-2024, 2015), may suffer even more significant changes then that projected earlier.

Brazil has the most renewable energy matrix in the industrialized world. About 41.2% of its production coming from renewable sources such as water resources, biomass and ethanol, wind and solar energy. The world energy matrix is composed of 13.5% of renewable sources in industrialized countries, decreasing to 6% in developing nations. The Brazilian biomass from sugarcane represents 16.9% of the national energy matrix (BEN, 2016). In the agreement signed during COP-21, Brazil committed to reduce the greenhouse gas (GHG) emissions by 37% and 43%, compared to the 2005 levels, by 2025 and 2030 respectively. The agreement will promote an irreversible change in the current Brazilian energy framework, and the sugarcane industry has a huge potential to replace the fossil fuels with ethanol to meet the needs established.

Brazil is the world's largest producer of sugarcane and the second largest producer of ethanol, only behind of the United States of America. In 2017, Brazil produced 657.18 million tons of sugarcane in 9.05 million hectares (ha) (CONAB, 2017). To meet the COP-21 goals, the ethanol production is expected to reach 54 billion of liters in 2030, almost double of the 2016 production. The sugar production is expected to increase from 38.7 million tons to 46.4 million tons by 2030. To meet these demands for ethanol and sugar production, the National Confederation of Industry (CNI), in partnership with the University of São Paulo (FEA/USP), estimated that it will be necessary 942 million tons of sugarcane per season in 2030 (CNI, 2017). To meet these demands, the Brazilian southeast region, especially São Paulo state, should still be the main pole of production, since the other Brazilian regions suffer with lack of investments in new research and technologies to increase their productions capacity.

From the agronomic point of view, two alternatives are possible. If the area expansion is possible, the increase of agricultural yield is also an alternative. Despite of the many controversies over the sugarcane expansion and their impact on food production (Popp et al., 2014), studies showed that there is still potential for the crop expansion, especially in pasture fields (Loarie et al., 2011). However, a more sustainable alternative from the economic and environmental viewpoint is increase the crop yield. For this, it will be necessary investment in technologies that allow to produce more in the same area, i.e., the crop yield should reach new levels and exceed the current Brazilian average of 73 Megagram (Mg) ha-1 (CONAB, 2017). In this context, precision agriculture (PA) is an approach that includes several technologies and tools that can contribute significantly to these challenges.

The PA is an approach that seeks to increase yield through a site-specific management of soil and crops, optimizing the inputs and environmental impacts (Bullock et al., 2007). The main technologies available to PA users are yield monitors, remote and proximal soil/plant sensors associated with Global Navigation Systems (GNSS) and several Geographic Information Systems (GIS) packages. Despite the several technologies available, the most used are the GNSS for automatic guidance the agricultural machines and the variable rate technology (VRT) to apply fertilizers, seeds, pesticides and herbicides. According to Erickson et al. (2017), in the USA dealership survey, 72% of the producers use GPS for automatic guidance/steering. Among the VRT technologies, application of limestone and nutrients are the most used, with 40% and 38%

respectively. Although these technologies are available worldwide, the Brazilian sugar and ethanol industry lacks the effective adoption of these tools. The adoption of PA is still far from its potential for localized management of sugarcane fields (Silva et al., 2011).

The present study aimed to evaluate the impacts on sugarcane production to reach the goals established for 2030, based on agreement signed during COP-21, assessing the role of PA technologies. The economic and environmental impacts to increase area and yield of sugarcane to reach the 2030 targets, were evaluated. Through the present study, it will be possible to visualize the main challenges that Brazil will face in the next decade, providing indicators to guide public policies that will overcome the technological bottlenecks for a sustainable sugarcane production expansion.

Material and Methods

To evaluate the economic and environmental impacts of the sugarcane production expansion, 4 scenarios were considered: 1) Current production in 2016/2017 season (labeled as ‘current – 2016’), 2) Area expansion with the current yield (labeled as ‘area – 2030’), 3) Yield increase with the current area (labeled as ‘yield – 2030’) and, 4) The adoption of PA technologies (labeled as ‘PA – 2030’). The PA technologies assessed were the field systematization and the VRT for fertilizers application. The following topics detail the characteristics applied to the assessment.

Sugarcane Production

The scenarios assessed were applied to São Paulo state, the main Brazilian producer (CONAB, 2017). São Paulo accounts for 49% of the Brazilian ethanol production and 62% of sugar production in 2016. About half of the harvested sugarcane production was destined for ethanol and the other for sugar production (48% and 52% respectively) in 2016/2017 season (CONAB, 2017). The average yield of São Paulo state in 2016 season was 77.50 Mg ha^{-1}, while the Brazilian average yield was 72.60 Mg ha^{-1}. The state of São Paulo accounts for 53% of the total sugarcane area in Brazil, with 4.77 million hectares (Table 1).

Table 1. Sugarcane current production (2016), planted area, average yield and sugar and ethanol production for Brazil and São Paulo state (CONAB, 2017).

	Production [10^3 Mg]	Area [10^3 ha]	Yield [Mg ha^{-1}]	Sugar [10^3 Mg]	Ethanol [10^3 l]
Brazil	657,184.00	9,049.00	72.6	38,691.1	27,807,523.00
São Paulo	369,925.00	4,773.00	77.5	24,059.8	13,702,767.00

Field systematization

Field systematization is a management practice that has been widely adopted in sugarcane fields by automatic guidance technologies enabled by GNSS (Global Navigation Satellite System) systems. The main objective is improving the field occupation and the parallelism between sugarcane planting rows, which allows greater efficiency of all agricultural operations (Medeiros Barbosa, 2010). For this, the sugarcane rows must be planned prior to the planting operation, considering the area dimensions, slope and landscape forms of the terrain. Adequate field systematization allows significant improvements in the parallelism of planting rows, rows length, field occupation and decreases in the amount of maneuvering necessary to machines cover the entire field. The present study evaluated three sugarcane fields localized at Santa Fé mill (Figure 1). The indicators of area, number of maneuvers and rows length, before and after of the field systematization, can be found in Table 2.

Table 2. Indicators of area occupation, maneuvers and sugarcane row length of fields evaluated before and after of the field systematization.

	Area (ha)				Maneuvers	Lenght (km)	
	Crop	Curves	Aisle	Total		Mean	Total
				Before			
Field 1	172.680	7.860	6.100	186.64	2384	0.499	1189.868
Field 2	166.060	4.980	5.400	176.44	2250	0.504	1134.369
Field 3	130.370	5.120	6.210	141.70	2786	0.322	895.9444
Mean	156.370	5.987	5.903	168.260	2473	0.442	1073.394
				After			
Field 1	177.360	2.060	7.220	186.64	2104	0.570	1199.441
Field 2	169.590	0.940	5.910	176.44	1878	0.610	1146.342
Field 3	130.750	4.280	6.670	141.70	2258	0.394	899.9308
Mean	159.233	2.427	6.600	168.260	2080	0.525	1081.905

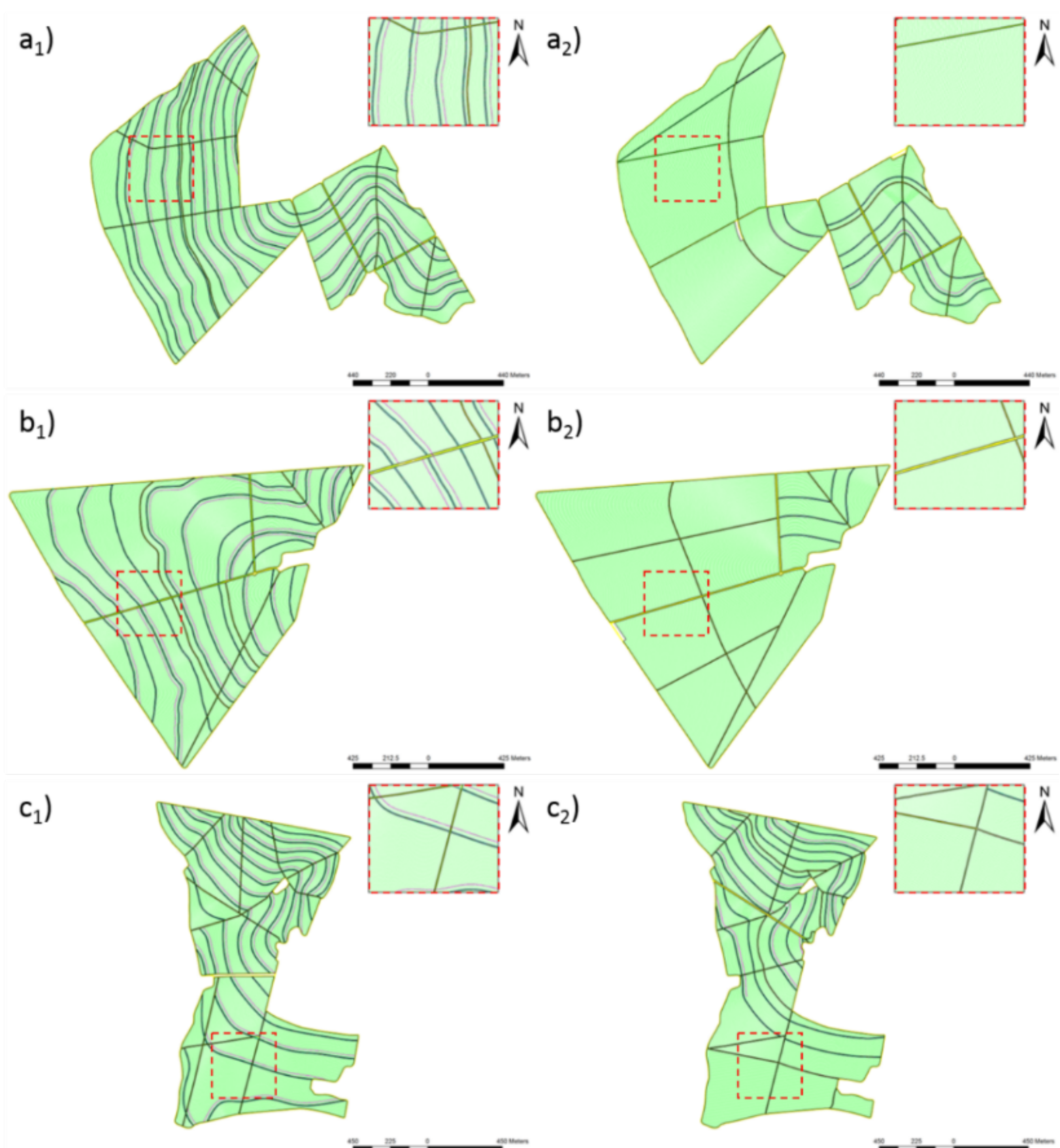

Figure 1. Before (1) and after (2) of the field systematization in sugarcane evaluated fields 1 (a), 2 (b) and 3 (c) (Source: Santa Fe Mill).

Variable rate technology (VRT) for fertilizers application

Since 2012, the precision ag group of Campinas State University (UNICAMP), in partnership with Brazilian sugarcane mills, has been evaluating indicators of yield and fertilizers spend in sugarcane fields where fixed and variable rates were applied (Table 3). Magalhães et al. (2014) showed the field research where some indicators are obtained.

Table 3. Indicators of yield and fertilizers spend in sugarcane fields where fixed and variable rates were adopted. The indicators were obtained in experimental fields assessed by Campinas State University group in partnership with sugarcane mills.

		Variable Rate	Fix Rate
Average yield	Mg ha^{-1} $year^{-1}$	80.80	79.70
Limestone	kg ha^{-1} $season^{-1}$	1452.00	1550.00
Gypsum	kg ha^{-1} $season^{-1}$	1178.00	1326.00
Fertilizers application (plant cane)			
N	kg ha^{-1}	61.60	83.20
P_2O_5	kg ha^{-1}	164.40	204.00
K_2O	kg ha^{-1}	157.20	125.00
Fertilizers application (ratoon)			
N	kg ha^{-1}	103.00	159.50
P_2O_5	kg ha^{-1}	7.10	0.00
K_2O	kg ha^{-1}	119.00	90.00

Economic and Environmental Assessment

The scenarios assessed were simulated on the Virtual Sugarcane Biorefinery (BVC) platform. The BVC platform, that was developed by CTBE/CNPEM (Bonomi et al., 2016), includes a database related to the sugarcane production costs, including all the operations required for planting, fertilizing, harvesting, loading, transportation, etc. To evaluate the agricultural phase, BVC has developed - and constantly updated - the CanaSoft model (Figure 2). The BVC allow technical, economic, social and environmental evaluations of the agricultural practices in the sugarcane production system (Cavalett et al., 2016).

To evaluate the scenarios, we considered the estimated production of 942 million tons of sugarcane in 2030. First scenario (current – 2016), used as the base scenario, correspond to the production of São Paulo state in 2016/2017 season. The second scenario (area – 2030) assess the area expansion needed to meet the sugar and ethanol demands by 2030, keeping current sugarcane yield unchanged. For this scenario, the average radius of production was calculated to satisfy the production required. The third scenario (yield – 2030) evaluated the inverse situation, keeping the area fixed and increase the yield needed to reach the goals. For this scenario, we considered an average radius of production of 35 km. Scenarios 2 and 3 aims to present the extremities of the possible sugarcane expansions, i.e., expansion of area and crop yield. Finally, for the scenario 4 (PA – 2030) the contribution of PA technologies was addressed according to the previously indicators (Tables 2 and 3).

To environmental assessment, the life cycle inventory generated by CanaSoft was used. The inventory comprises all sugarcane production operations, including the amount and materials involved, such as the fuel consumption and the quantity and type of inputs applied to fields (Bonomi et al., 2016). The environmental impacts were evaluated through the Life Cycle Analysis (LCA) using SimaPro® software (PRé ConsultantsB.V.) and the ReCiPe Midpoint (H) V1.05 method (ISO, 2006a; 2006b). We considered the climate change (kg CO_2 eq.) category in the environmental assessment. All dataset and indicators presented here are stored in the Agronomic Database (BDAgro) described in Driemeier et al. (2016). For all scenarios assessed, we adopted a mill with 4 million tons of milling capacity and a sugarcane cycle of 5 years. For the simulations at São Paulo state, the proportions were remained according to 2016 Brazilian production.

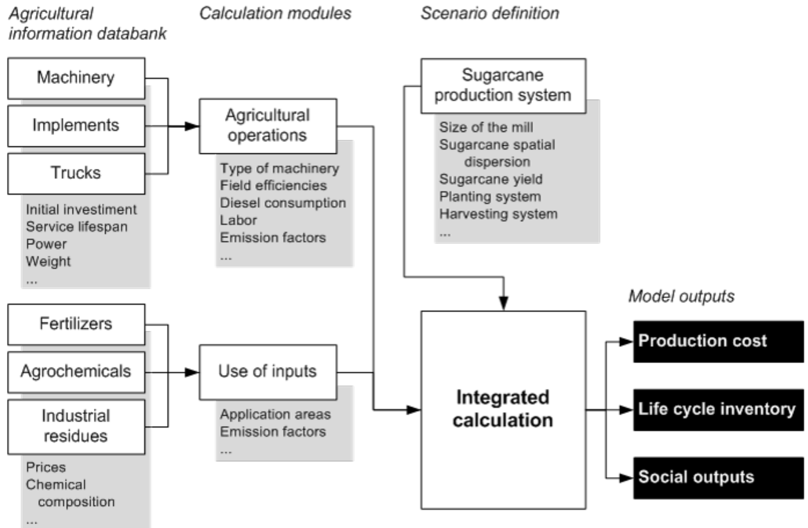

Figure 2. CanaSoft model scheme. Source: Bonomi et al. (2016).

Results

Keeping the production proportions between São Paulo and Brazil, 531 million tons of sugarcane should be produced in 2030 by São Paulo state. This value represents an increase of 43% compared to the 2016 production. Setting the 2016 average yield of 77.50 Mg ha^{-1}, an expansion from 4.77 to 6.85 million hectares should be necessary in São Paulo state (scenario 2 - 'area – 2030'), an increase of about 2 million hectares (Figure 3). On the other hand, setting the current production area, would be required an average yield of about 111.00 Mg ha^{-1} in 2030 to reach the goals (scenario 'yield – 2030'). The average gains proportioned by PA technologies (scenario 'PA – 2030') showed a reduction in the area needed to 6.34 million hectares, mainly due to the yield increases from 77.50 to 83.70 Mg ha^{-1}. The field systematization, on average, increased 8.5 km in sugarcane planting rows in the evaluated fields. In addition, the average row length increased to 525 m, when compared to 442 m before the field systematization. This fact means, on average, a reduction about 16% in the number of required maneuvers (from 2473 to 2080) and in the best area occupation by the reduction of field dedicated to contour rows (Table 2).

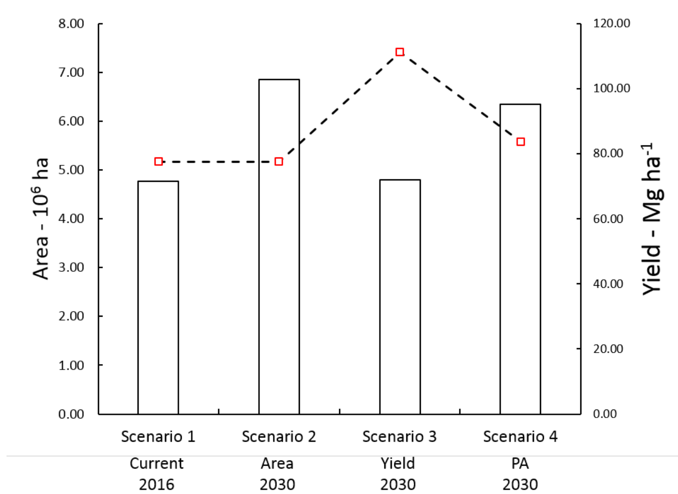

Figure 3. Area expansion (columns) and average yield (dashed line) needed to reach the goals set for 2030 in the scenarios assessed.

Increase only the yield was the best option from economic point of view. The current cost was reduced from USD22.95 to USD16.39 per Mg of sugarcane produced (Figure 4), a reduction about 29% in the total cost. On the other hand, increasing only area promoted an increase in the production cost from USD22.95 to USD23.37 per Mg of sugarcane produced (scenario ‘area – 2030’). The adoption of PA technologies provided a reduction about 11% in the total production costs (from USD22.95 to USD20.37 Mg^{-1}). The fertilizers application at variable rates allowed the reduction of limestone and gypsum applications throughout the crop cycle when compared with fixed rates (Table 3), a difference of 98.00 kg ha^{-1} and 148.00 kg ha^{-1} per crop cycle respectively. A significant difference was observed in the nitrogen (N) application by variable rates, with a difference of 21.60 kg ha^{-1} and 56.50 kg ha^{-1} in the plant cane and ratoon respectively. Potassium requirements have always higher for the whole crop cycle in the variable rate applications, while for phosphorus the main difference was observed in the plant cane application, with higher amounts applied for the fixed rate (difference of 39.60 kg ha^{-1}).

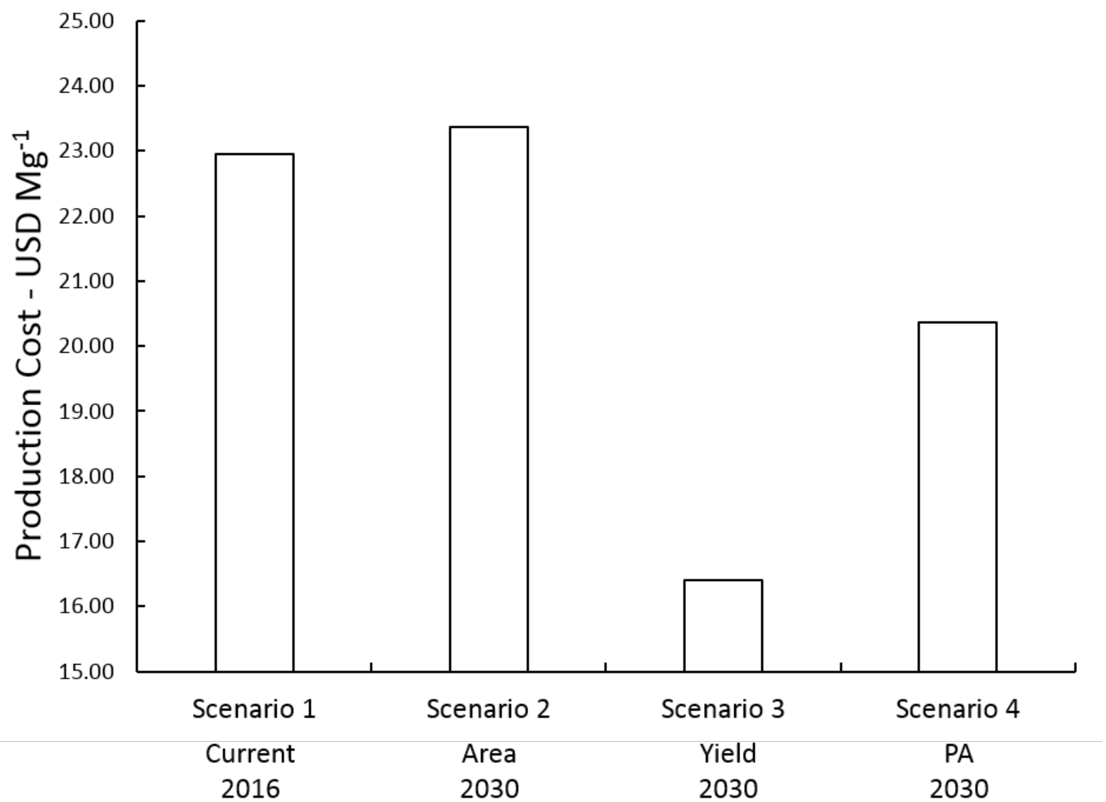

Figure 4. Total sugarcane production cost (USD Mg^{-1}) for the scenarios assessed to reach the goals set for 2030.

According to the environmental impacts associated with the sugarcane production, the scenario 2 (area – 2030) showed the worst indicators (Figure 5). Increase only the planted area to reach the 2030 targets produced greater impacts on climate change, corresponding to 41.54 kg CO_2 eq. per ton of sugarcane produced. On the other hand, increase only the yield (scenario ‘yield – 2030’) showed the best indicators, corresponding to 75% of the environmental impacts compared to the worst scenario (area – 2030).

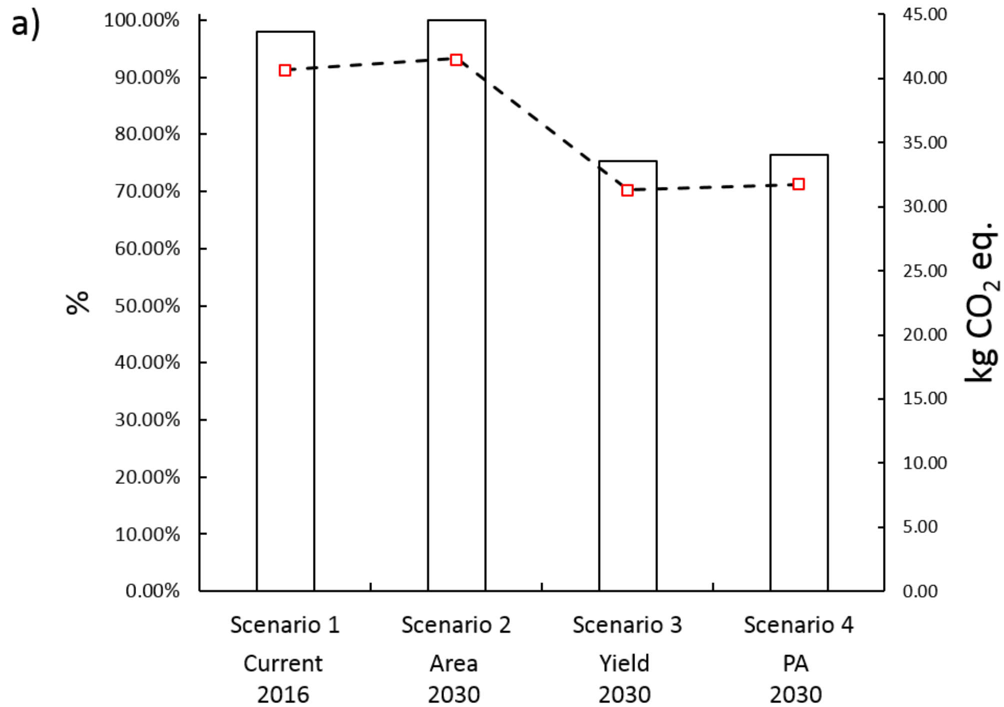

Figure 5. Assessment of environmental impacts for climate change (kg CO_2 eq.) in the scenarios assessed. Relative contribution (columns) and absolute values (dashed line), per Mg of sugarcane production, of the indicators.

In terms of climate change, scenario 'PA – 2030' was very similar to scenario 3, with a difference of 1%. Furthermore, the PA scenario presents lower values for production and use of fertilizers and other agrochemicals, due to the lower application of inputs by VRT (Table 4). The last scenario (scenario 4) assessed showed the great contribution of PA technologies to mitigate the climate effects. The current scenario of sugarcane production corresponds, per ton of sugarcane produced, to 40.7 kg CO_2 eq. for climate change.

Table 4. Climate change impacts (kg CO_2 eq.) of the evaluated scenarios per Mg sugarcane stalk produced.

	Scenario 1 current-2016	Scenario 2 area - 2030	Scenario 3 yield - 2030	Scenario 4 PA - 2030
Fertilizers and agrochemicals - Production	6.1	6.1	3.8	3.6
Fertilizers, agrochemicals and residues - Use	21.3	21.3	16.9	15.4
Diesel	6.6	6.6	4.5	5.6
Vinasse - Transport and application	1.2	1.3	0.9	1.1
Sugarcane transport	3.3	4	3.3	3.8
Others	2.2	2.3	1.8	2.1
Total	**40.7**	**41.5**	**31.3**	**31.7**

Discussion

The current Brazilian agricultural scenario shows that the adoption of PA increases every year for all Brazilian agribusiness segments. However, the sugarcane crop presented a low adoption of PA practices as reported by Silva et al. (2011). The large adoption of PA in grain crops, like maize and wheat, can be one of the reasons for the advancement of these crops against sugarcane. In the last decades, maize and wheat showed an expressive growth in the yield when compared with sugarcane (Figure 6). While maize and wheat crops showed yield increases about 30% and

19% from 2000 (4.76 to 6.20 Mg ha^{-1} and 3.00 to 3.60 Mg ha^{-1}, respectively, for maize and wheat), sugarcane showed a growth of 8% (71.23 to 76.82 Mg ha^{-1}) in the same period. The genetic improvement of these crops can be one of the main reasons (Tian et al., 2011), unlike in sugarcane where little genetic improvements was made in the last years. In addition, a sugarcane yield decline can be observed since 2008. The intensive adoption of sugarcane harvesting mechanization, since 2008, can be one of the explanations of the yield decline (Franco et al., 2018). The lack of PA technologies adoption in the Brazilian sugarcane sector may have contribute to the yield stagnation in the last decade, not exceeding 80 Mg ha^{-1} of average yield.

A significantly change in the current scenario of yield stagnation can be observed by the producers who are adopting technologies of automatic guidance/steering allowed by GNSS. The indicators presented here showed that the field systematization can optimize the use of fields to increase the efficiency of agricultural operations (Table 2). One of the great advantages of the field systematization is observed by the number of maneuvers to cover the entire field. On average, a reduction about 16% (393 maneuvers) was observed, translating into greater operational efficiency for all agricultural operations. As reported by Spekken et al. (2015), the maneuvers are a small fraction of the production cost, but they have a great impact on the final economic revenue. According to the same authors, sugarcane planting rows with lengths lower than 50 m do not generate enough revenues to pay the costs of sugarcane harvesters maneuvers.

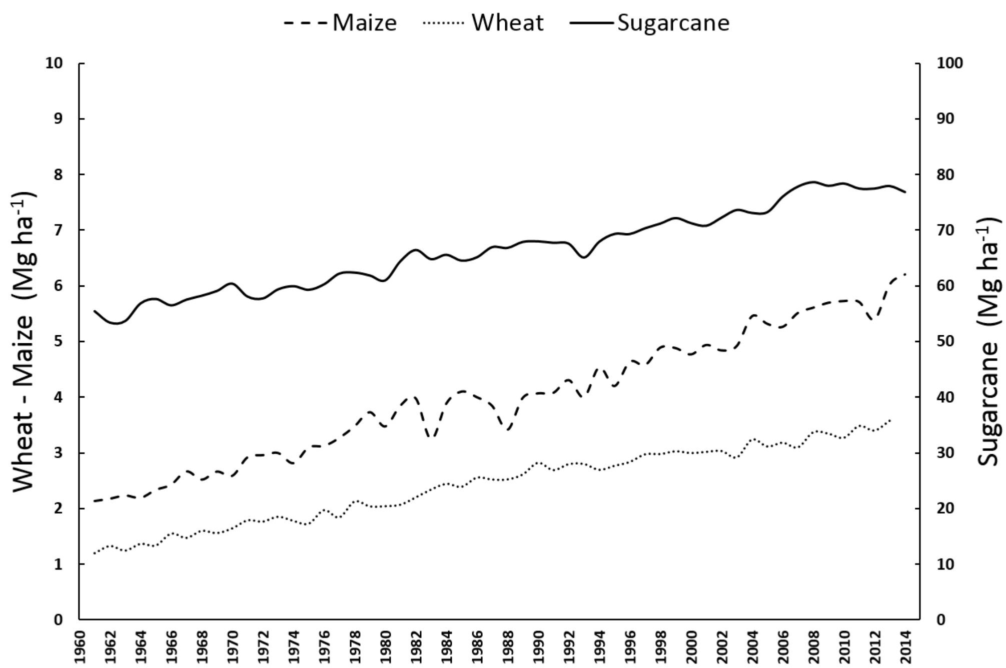

Figure 6. Yield (Mg ha^{-1}) of wheat, maize and sugarcane crops from 1961 to 2014. Source: FAOSTAT, 2016.

On the other hand, the VRT to apply fertilizers is also an important tool that can contribute to the sugarcane production sustainability. Brazil experienced significant increases in fertilizer consumption in the last decade compared with other countries. In 2015, about 14 million tons of N-P-K fertilizers were consumed, 50% higher than the previous decade (IPNI, 2016). Sugarcane was responsible for 10% of the total N-P-K consumption. The indicators showed here evidence a reduction in fertilizers required for crop (Table 3). This can contribute to the reduction of Brazilian fertilizer imports. Although the yield not increased by VRT, the results showed the same amount of biomass produced applying smaller amounts of inputs. Among the fertilizers, nitrogen was the ones that showed the largest difference between fixed and variable rates, a difference of 21.6 kg ha^{-1} and 56.5 kg ha^{-1} for plant cane and ratoon respectively. Many studies reported in the literature aimed to investigate the best rates of nitrogen application in crops, especially in sugarcane (Ambrosano et al., 2005; Ambrosano et al., 2011). However, there are few studies in the literature that reported the benefits of VRT for nitrogen application in sugarcane fields. Some studies reported the nitrogen application in sugarcane fields by canopy reflectance sensors (Amaral et al., 2015, Colaço et al., 2012) or by yield monitors (Magalhães et al., 2014). Despite the recent advances, Otto et al. (2016) reported the discrepancies in the nitrogen recommendations for sugarcane in a comprehensive literature review. For sugarcane is recommended a rate between 120 and 200 kg ha^{-1} of N in the Brazilian conditions (Cantarella and Rossetto, 2014). These values are above of the indicators presented here. Thus, long-term studies on sugarcane could be investigated to review the N fertilizer recommendations, considering the intrinsic spatial variability of the fields.

To Brazil achieve the goals set for 2030, São Paulo should be produce 531 million tons of sugarcane. An increase of 2 million ha in planted area is needed if yield remain constant. Thus, sugarcane fields should also expand to new Brazilian states. On the other hand, keeping the production area at 4.77 million ha, an average yield of 111 Mg ha^{-1} would be required by 2030. Reach this yield level seems to be faraway, but investment in technology and research can contribute significantly, since the genetic potential of the crop is 300 Mg ha^{-1} (Waclawovsky et al., 2010). For the expansion of area or yield needed, annual growth rates of 3% would be required until 2030. This goal is not impossible to achieve, since Brazil and the São Paulo state presented, respectively, growth's rate of 8% and 6% in planted area in 2010/2011 season (CONAB, 2011). The average growth rate in planted area in the last six seasons of the Brazilian southeast region (2010 to 2016) was 2.9%. Thus, an annual growth rate of 3% does not become technically unfeasible, where more detailed studies should be carried out.

The yield increases represented a more feasible option from the economic point of view. From the current average cost of USD22.95 Mg^{-1}, increasing yield to levels of 111 Mg ha^{-1} means a reduction of 29% in the production costs, corresponding to USD16.39 Mg^{-1} (Figure 4). A major contribution to increase yield and reduce production costs is the field systematization and the VRT for fertilizers application, where production costs reduces to USD20.37 Mg^{-1}. Although the indicators presented here do not showed yield increases due to the fertilizer application at variable rates, like reported in long-term studies in grains (Yost et al., 2016), the production costs can be reduced through the inputs rationalization. The field systematization is one of the main factors that are responsible for yield increases to 83.7 Mg ha^{-1} in the scenario 'PA-2030' assessed. The yield increases of 8% is still far from the growth observed by maize and wheat in the last decades. But the results showed that increase the sugarcane yield translated into a reduction of 500,000 ha needed to meet the demands by 2030. In addition to PA technologies, the production of second generation ethanol (Aditaya et al., 2016) will also contribute significantly to meet the demands of ethanol production by 2030, reducing the area expansion needed.

In addition, the adoption of PA technologies allowed a significant reduction in environmental impacts, observed by indicators of climate change. Increasing only the yield (scenario yield-2030) showed a small difference when compared to the PA adoption (scenario 4). Considering the intrinsic soil spatial variability to apply fertilizers at variable rates proved to be a sustainable way like increasing yield to 111 Mg ha^{-1}. The results can be attributed mainly to the maneuvers reduction, which reduces the diesel consumption of machines, and the reduction of nitrogen fertilizer application, responsible for N_2O emissions (Crutzen et al., 2008; de Vries and Bardgett, 2012; Soares et al., 2015). The correct use of nutrients, as proposed by 4R principle (right amount, right place, right source and right time) by the International Plant Nutrition Institution (IPNI), should be a priority to achieve lower environmental impacts. Furthermore, the adoption of PA and VRT to apply fertilizers can contribute significantly to reduce the environmental pollution and fertilizers imports by Brazil.

In the current world scenario, where resources are increasingly scarce and environmental pollution increasing, the PA adoption will be fundamental. São Paulo state will still be responsible for the major sugarcane production in the country. The results showed that the area and/or yield expansion not considering the sustainable management alternatives, like PA technologies, are not the best options from the environmental point of view. The sugarcane yield stagnation in the last five years must be addressed, where the PA and other technologies improvements should guide the agenda of government and producers.

Conclusion

The findings showed that the PA adoption in Brazilian sugarcane sector is very far from its full potential for site-specific management. The results showed that an expansion of 2 million ha would be required to reach the goals if the current yield was remained, suggesting that the expansion should be in other Brazilian states as well. The adoption of Global Navigation Satellite System (GNSS) to guide the agricultural machines and Variable Rate Technologies (VRT) generates gains around 11% in total production cost, increasing the Brazilian sugarcane average yield to 83.7 Mg ha^{-1}. From the environmental point of view, the adoption of PA technologies can reduce around 20% of climate change and fossil depletion compared with the current scenario of 2016, essential to reach the greenhouse gases (GHG) reduction goals. Manage spatial and temporal variability of crops and soils will allow maximize the sugarcane production, reducing production costs and environmental impacts through the rational use of inputs.

Acknowledgments

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