GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012) **4**, 119–126, doi: 10.1111/j.1757-1707.2011.01122.x

OPINION

Ethanol from sugarcane in Brazil: a 'midway' strategy for increasing ethanol production while maximizing environmental benefits

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Abstract

This article reviews the history and current state of ethanol production from sugarcane in Brazil and presents a strategy for improving ecosystem services and production. We propose that it is possible to produce ethanol from sugarcane while maintaining or even recovering some of Brazil's unique neotropical biodiversity and ecosystem climate services. This approach to the future of sustainable and responsible ethanol production is termed the 'midway' strategy. The 'midway' strategy involves producing the necessary biotechnology to increase productivity while synergistically protecting and regenerating rainforest. Three main areas of scientific and technological advance that are key to realizing the 'midway' strategy are: (i) improving the quality of scientific data on sugarcane biology as pertains to its use as a bioenergy crop; (ii) developing technologies for the use of bagasse for cellulosic ethanol; and (iii) developing policies to improve the ecosystem services associated with sugarcane landscapes. This article discusses these three issues in the general context of biofuels production and highlights examples of scientific achievements that are already leading towards the 'midway' strategy.

Keywords: agroecosystems, bioenergy, biofuels, cell wall, cellulosic ethanol, ethanol, greenhouse gas value, land use, sugarcane, sustainability

Received 4 June 2011 and accepted 8 July 2011

Introduction

Sugarcane is a highly productive land plant that uses the C_4 pathway of photosynthesis, which confers higher potential light, water and nitrogen use efficiencies, than the alternative C_3 pathway (De Souza & Buckeridge, 2010). Sugarcane was first introduced to Brazil in 1532 and, because of the favorable climate and soil conditions, it quickly became an important sugar production crop for exportation to Europe (Dinardo-Miranda *et al.*, 2008). Sugarcane's success in many regions of Brazil is due to the C_4 system being well adapted to the tropical climate conditions. São Paulo and the adjacent states are particularly suitable for sugarcane cultivation, accounting for the 85% of sugarcane currently cultivated in Brazil (Goldemberg, 2007). In the beginning, the sugarcane industry was based on wild species, but in 1888 the Dutch began breeding wild sugarcane and established a selection of varieties in Java, Indonesia, which led to commercial production of the first cultivar in 1921 (Moore, 2005). Since then, several cultivars have been developed and play an important role in the economy of tropical and sub-tropical regions.

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Economic problems in the 1970s, generated by the oil crisis, led Brazil to start a program to substitute ethanol for gasoline (the Pro-alcohol Program) to decrease economic and political dependence on foreign oil (Macedo *et al.*, 2008). This program encouraged ethanol production from diverse sources, but economical and historical reasons led to the adoption of sugarcane as the primary feedstock for Brazilian ethanol production.

The sugarcane industry reached high efficiency (ethanol production at low cost) in the 1980s and 1990s, and sugarcane ethanol currently accounts for the vast majority of Brazil's biofuels. In the 1970s, the incompatibility of ethanol with commercial vehicle engines represented a technological barrier called the 'blending wall', which limited the amount of ethanol that could be mixed with gasoline. In 2003, the widespread commercial introduction of vehicles designed to run off of both gasoline and ethanol, termed 'FlexFuel' vehicles, overcame the technological limitation related to the blending wall and facilitated the decrease in gasoline use within the country (BNDES, CGEE, 2008). This new technology has allowed Brazil to reduce the proportion of transport fuel coming from gasoline, thereby reducing the nation's CO_2 emissions. Yet, to achieve the climate benefits of a renewable fuel and maintain the sustainability of sugarcane ethanol production, much higher productivity and production efficiency will be required, demanding increases in yield and conversion efficiency. Although both can be improved by research on C_4 photosynthesis, it is important to note that there is considerably more energy in sugarcane than what is currently used for the production of ethanol from sucrose. In fact, only one-third of the biomass from sugarcane is transformed into ethanol, while the remaining two-thirds are left as bagasse and sugarcane straw (Goldemberg, 2008). Currently, the sugarcane agro industry combusts the bagasse, in a process called cogeneration, to provide power for the machinery and heat for processing and distillation. The excess heat energy is used to generate bioelectricity, thus allowing the biorefinery to be self-sufficient in energy utilization (BNDES, CGEE, 2008). In 2005/2006, the production of bioelectricity was estimated to be 9.2 kWh per ton of sugarcane (Macedo *et al.*, 2008), approximately 2% of Brazil's total energy generation production (MME – Ministério de Minas e Energia, 2008). Although the prospects of energy production by sugarcane industry are very promising, the increase in global ethanol demand, driven by global concern for addressing climate change, has led to the development of new hydrolytic processes to convert cellulose and hemicelluloses to ethanol (Buckeridge *et al.*, 2010; Dos Santos *et al.*, 2011). An increase in convertible biomass would decrease the land area requirement for biomass crops, thus diminishing social (e.g. negative health effects due the burning process, poor labor conditions) and environmental impacts (e.g. loss of biodiversity, water and land uses) and at the same time improving the economic potential of sugarcane.

Three main areas of scientific and technological advance will be critical to achieving these goals. First, improved scientific understanding of the physiology and molecular biology of sugarcane, with specific focus on its use for bioenergy production, will provide strategies for maximizing yield. Second, development of technology for the production of cellulosic ethanol will greatly increase the potential ethanol yield of sugarcane. Third, improved scientific knowledge of the agronomy and ecology of sugarcane can be applied to improve the ecosystem services associated with sugarcane production. This article deals with these three potential targets for the future of biotechnology for biofuels. On the basis of these three goals, we propose a 'midway' strategy, which consists of continuing to form a strong scientific basis for the development of sustainable and socially responsible ethanol production through the combined efforts of genetic improvement of sugarcane, physiological understanding, improvement of production processes, and sensible landscape management.

Improving the scientific understanding of the physiology and molecular biology of sugarcane with specific focus on its use for bioenergy production

Relatives of sugarcane (*Saccharum officinarum*) and hybrids of this species grow on almost all continents. Over the course of history, human populations have selected plants from the genus *Saccharum* to maximize harvestable sugar (Flandrin & Montanari, 1996). After the Portuguese brought sugarcane to Brazil, the development focused on producing cultivars with progressively higher yields and sucrose levels, culminating in the modern cultivars used today. Although the focus of genetic improvement was to increase sugar content, some physiological parameters such as mineral nutrition, growth rate, and tolerance to water stress and diseases have been included in selective breeding programs (Dinardo-Miranda *et al.*, 2008; Loureiro *et al.*, 2010).

Photosynthesis research is key for improving conversion and biomass production. Although C_4 photosynthesis was first discovered in sugarcane (Hatch & Slack, 1966), maize (also a C_4 plant) has become the principal model for C_4 physiology and, at present, relatively little is known about sugarcane photosynthesis. Nonetheless, since the 1960s, sucrose accumulation in culms of sugarcane has been a focus area of research, and models of this process have been developed (for reviews see Moore, 1995; Grof & Campbell, 2001).

Models of sugar storage mechanisms in sugarcane have been proposed (Moore, 1995), and several approaches to using molecular biology tools to increase sucrose in sugarcane stems have been suggested (Grof & Campbell, 2001). Although genetic transformation of sugarcane can be difficult (Waclawovsky *et al.*, 2010), successful transformations have been performed beginning in 1992 (Bower & Birch, 1992). These have led to interesting results, such as the introduction of a sucrose isomerase gene that caused sugarcane culms to produce the sucrose isomer isomaltulose, which enables this tissue to accumulate twice as much sugar (Wu & Birch, 2007), and the introduction of three cellulolytic enzymes genes that can facilitate cellulosic ethanol production (Harrison *et al.*, 2011). At the same time, '-omics' tools have been used to understand sucrose accumulation mechanisms in sugarcane (Glassop *et al.*, 2007). These techniques may lead to better models to explain and consequently acquire control over sucrose production in sugarcane.

The integration of the information from studies of gene expression into physiological research could be a powerful strategy to achieve higher yields, sucrose content and stress reduction (Buckeridge *et al.*, 2010; Hotta *et al.*, 2010). But such a task is not easy and will require taking sugarcane into the synthetic biology era, hopefully verifying the proposition that sugarcane has a potential to store up to 25% of sucrose (Bull & Glasziou, 1963), which is twice the average concentration found nowadays.

With increasing demand for bioenergy, new routes to increase ethanol production from grasses are now being investigated (Buckeridge *et al.*, 2010). There is potential to retrieve far more energy from bagasse and straw of grasses, including sugarcane, by converting this lignocellulosic material to ethanol (Soccol *et al.*, 2010). Bagasse and straw are composed primarily of cell walls that could be used as sources of carbohydrates for bioenergy production through biological fermentation or thermochemical conversion (Buckeridge *et al.*, 2010; Dos Santos *et al.*, 2011). Therefore, it is also necessary to understand sugarcane cell wall polysaccharide structure and properties. It is equally important to understand cell wall metabolism (both biosynthesis and degradation). Sugarcane bagasse is 44–46% cellulose (Sun *et al.*, 2004) and ~27% hemicelluloses (G.J. Rocha, personal communication).

Given that the control of sucrose storage in sugarcane is quite well understood, one could readily establish targets for increasing the accumulation of carbohydrates in this plant. One potential target is increasing the cell wall proportion. Biosynthesis could be genetically manipulated to produce thicker cell walls that would look like storage cell walls (Buckeridge, 2010). An obvious candidate for increasing biomass in sugarcane is the mixed linkage-beta-glucan, which is in fact a storage polymer in seeds of grasses such as maize (Buckeridge *et al.*, 2004). In spite of the fact that changing cell wall biosynthesis can be as difficult as increasing sucrose in the vacuoles of sugarcane culm, the advantage of making thicker cell walls is that they can compact sugars to a density that is thought to be higher than that of the vacuoles. A second potential target is the integration of a cell wall degradation mechanism analogous to the ones found in endosperms and cotyledons (Buckeridge, 2010) so that the polymers could be efficiently transformed into fermentable sugars *in vivo*. As in the case of the sucrose increasing strategies, the wall manipulation in sugarcane will require the use of synthetic biology techniques.

Developing technologies for second generation ethanol

Currently, approximately two-thirds of sugarcane's biomass is not used for ethanol production (Goldemberg, 2008). Instead, the bagasse is combusted to produce electricity (BNDES, CGEE, 2008; Cortez *et al.*, 2008). Although burning for electricity production has greatly improved the sugarcane biorefinery efficiency, even higher efficiency is possible if this bagasse were converted to cellulosic ethanol (Buckeridge *et al.*, 2010). However, converting lignocellulose to ethanol is not straightforward. The cellulose and hemicellulose polymers that can be hydrolyzed are associated in a very complex composite in the cell wall (Carpita & McCann, 2000). As relatively little is known about the structure and architecture of the sugarcane cell wall, it is necessary to understand several aspects of the fine structure and metabolism of the principal hemicelluloses of sugarcane (arabinoxylan and mixed-linkage glucan) (Saavedra *et al.*, 1988). Furthermore, as more is learned about cell wall structure, enzymes and genes in microorganisms that efficiently hydrolyze these plant cell walls need to be identified. Phenolics that cross-link cell wall polymers should also be studied with the aim of increasing accessibility to polysaccharides and decreasing enzyme inhibition (Dos Santos *et al.*, 2008). However, as the cellulosic ethanol industry grows, high value co-products derived from hemicelluloses and phenolic compounds can be discovered and used for food, pharmaceutics, cosmetics and other industrial sectors.

In the next decade, four routes can be pursued to produce ethanol from lignocellulose, and therefore sugarcane bagasse: (i) chemical hydrolysis; (ii) enzymatic hydrolysis; (iii) autohydrolysis; and (iv) pentose fermentation (Buckeridge *et al.*, 2010).

In route 1 (chemical hydrolysis), the cell walls of sugarcane would be subjected to acid treatment to loosen the cell wall and provide a means to produce free fermentable sugars and oligomers. In this case, free-fermentable sugars do not include pentoses. At this point, the free-fermentable sugars would be converted in the same way that sucrose is currently converted to ethanol.

Route 2 (enzymatic hydrolysis) associates acid hydrolysis or other chemical or mechanical pre-treatments with enzymatic hydrolysis. Hydrolysis by enzymes from microorganisms is being explored using collections from a variety of sources including cow rumen, termite stomachs, and fungal and bacterial sources (Weng *et al.*, 2008; Weimer *et al.*, 2009; Xiang & Zhou, 2009; Buckeridge *et al.*, 2010; Soccol *et al.*, 2010). Either isolated or in combination with acid hydrolysis or mechanical pretreatment, biological conversion is expected to increase the efficiency of cellulosic ethanol production (Cheng *et al*., 2008). In Brazil, fungi have been the focus of research on microbial enzymes that can hydrolyze plant cell wall polysaccharides (Buckeridge *et al*., 2010; Polizeli *et al*., 2010). Laboratory studies with sugarcane straw demonstrated that fungi can be useful in lignocellulosic material degradation (Singh *et al*., 2008). However, until recently, sugarcane straw was burnt in Brazil and, consequently, little is known about its composition and potential for utilization in ethanol production.

At the same time as new enzymes are prospected and tested for biomass degradation, there is yet another route towards efficiency. Optimizing the metabolic pathways of microorganisms and fungi through genetic engineering or by finding appropriate yeast strains can improve the economics and yield of the cellulose-to-ethanol conversion processes. However, acquiring such control will require a better understanding of how different hydrolases act on cell wall polysaccharides (Moreira *et al*., 2010).

Route 3 (autohydrolysis) is the use of biomass from genetically engineered plants alternatively coupled with chemical pre-treatment or enzymatic hydrolysis. Autohydrolysis combines chemical hydrolysis and enzymatic hydrolysis but further uses the biological system of the plant itself to control the metabolic routes related to cell wall biosynthesis and degradation, rendering the plant with materials intrinsically easier to hydrolyze (Buckeridge *et al*., 2010; Xin *et al*., 2010). This could be achieved by genetically transforming the plant so that its cell walls become partially hydrolyzable before or just after harvesting (Ragauskas *et al*., 2006). Following this idea, Hartati *et al*. (2008) overexpressed cellulose in poplar, resulting into higher efficiency of hydrolysis and changes in growth and development. In addition, a corn variety capable of hydrolyzing its own cell walls has recently been produced (McKenna, 2008). For sugarcane, due to the difficulty in obtaining stable genetic transformation, an alternative would be the development of new varieties with modified cell walls without compromised sucrose productivity. The search for these varieties is underway in Brazil (Loureiro *et al*., 2010).

Route 4 refers to technological development to ferment pentoses efficiently and is complementary to the other three routes. Currently, most pretreatments of bagasse and trash destroy or leach out most hemicelluloses (Cheng *et al*., 2008; Singh *et al*., 2008; Chen *et al*., 2010; Soccol *et al*., 2010). This part of the industrial process could be modified to preserve hemicelluloses, and arabinose and xylose from arabinoxylan could be also used as sources of carbohydrates for fermentation. These pentoses would have to be efficiently fermented by yeasts used for ethanol production. To achieve this goal, some key steps need to be clarified so that strains of yeast *Saccharomyces* could be subjected to genetic engineering and become able to metabolize pentoses more efficiently (Goldman, 2010).

Applying improved scientific knowledge about agronomy and ecology of sugarcane to improve ecosystem services associated with sugarcane production

Minimization of the sugarcane industry's impacts on biodiversity and the environment will improve its sustainability and increase public approval. As demand for ethanol increases, increasing production will result in greater demand for land for sugarcane production. An expansion of land under sugarcane production is likely, especially in Brazil's Central-South region (Centro de Gestão de Estudos Estratégicos, 2006; Lapola *et al*., 2010). Part of the Central-South region is already occupied with sugarcane and soybean plantations, as well as land for livestock production. However, this region also includes the *cerrado* (savannah) biome, which requires protection in the face of expanding agriculture (Sawyer, 2008). Furthermore, although there are no current plans for expansion of sugarcane production in the Amazon (BNDES, CGEE, 2008), it is important to ensure the protection of this unique and valuable region of northern Brazil as sugarcane grows into a commodity and policy is formed (Sawyer, 2008).

It is hoped that genetic improvements will lead to higher yield on land already in sugarcane production, thereby minimizing land expansion. If carefully managed, sugarcane ethanol in Brazil probably does not pose a substantial threat to the rain forest in the Amazon but can rather be considered as an economic opportunity (Goodman, 2008; Lapola *et al*., 2010). For example, substantive increases in sugarcane yield (discussed above) or reduction of rangeland area through increased cattle density (Lapola *et al*., 2010) could allow for increased ethanol production while avoiding deforestation. In the absence of protective policies, however, sugarcane expansion may threaten forests through direct or indirect land use change (Sawyer, 2008; Lapola *et al*., 2010).

In addition to potential yield increases through the introduction of new and more productive sugarcane cultivars, sugarcane yield may increase because of climatic changes. In particular, the elevation of atmospheric CO_2 concentration (De Souza *et al*., 2008) and temperature (Vu & Allen, 2009) are both projected to increase the productivity of sugarcane, which is unique in that it is one of Brazil's few crops whose productivity is not expected to decline as a result of climate change (De Lucena *et al*., 2009; DaMatta *et al*., 2010). These climate-driven yield increases may help to reduce the land area required to meet increasing demand for sugarcane ethanol.

Brazil's 'Forest Code' currently mandates that, outside of the Amazon region, 20% of agricultural land be preserved as forest. While this law is not always strictly followed, sugarcane landscapes in Brazil are interspersed with forests, as well as eucalyptus plantations in several regions in São Paulo (Pinto *et al.*, 2003, 2005a, b). Mixed landscapes containing sugarcane and forest patches have enhanced biological diversity and improved biological, chemical and physical soil properties. This system also facilitates the maintenance of water in the soil, reduces the necessity of fertilizers and pesticides, and reduces the possibility of erosion (Soares *et al.*, 2009).

Another major benefit of having mixed landscapes composed of sugarcane and native forests is the potential to provide climate regulation services through sequestration and storage of carbon. Whereas aboveground carbon stocks in sugarcane crops average 7.4 tons of carbon per hectare over the course of a year, one hectare of forest can store *c.* 130–140 tons per ha (Gibbs *et al.*, 2007; Vieira *et al.*, 2008), 18 times more than what is found in sugarcane plantation. Regenerating tropical forests begin with low carbon storage but act as strong carbon sinks, typically accumulating 2–8 t C ha^{-1} yr^{-1} (Anderson *et al.*, 2006). Therefore, both mature and regenerating forests have high greenhouse gas values (*GHGV*; Anderson-Teixeira & DeLucia, 2011); the GHG benefit of maintaining a mature forest for 30 years is 870 t CO_2-eq ha^{-1} 30 yr^{-1}, while the *GHGV* of regrowing forests is 430 t CO_2-eq ha^{-1} 30 yr^{-1} (Fig. 1a). In contrast, sugarcane crops have *GHGV*s of -16 and 43 t CO_2-eq ha^{-1} 30 yr^{-1} for burned and mechanically harvested fields respectively. As a result, the greenhouse gas benefits of sugarcane production landscapes are greatly enhanced by the existence of forest patches (Fig. 1b).

Preservation or regeneration of forest fragments within agricultural landscapes would help to reduce negative impacts of projected sugarcane expansion on the biomes where such expansion will occur and could even lead to the recovery of land currently under sugarcane production. Indeed, Tabarelli & Roda (2005) suggest that conservation of biodiversity in regions where commodities and sugarcane crops are grown could benefit from an alliance between crops and forest fragments. Overall, forest patches in sugarcane landscapes provide the opportunity to re-establish biodiversity and ecosystem services.

Of course, effective application of the midway strategy must also consider other factors such as the economical aspects related to bioethanol production. For example, the addition of more forest within sugarcane cropping areas will increase the distance for transportation of raw material and also the produced bioethanol. This will lead to more emissions from transportation and could decrease the benefits of the accumulation of carbon by forests. Another important issue is the pattern of distribution of forests in the field. Further study will be required to determine optimal landscape patterns that allow for an efficient harvesting process

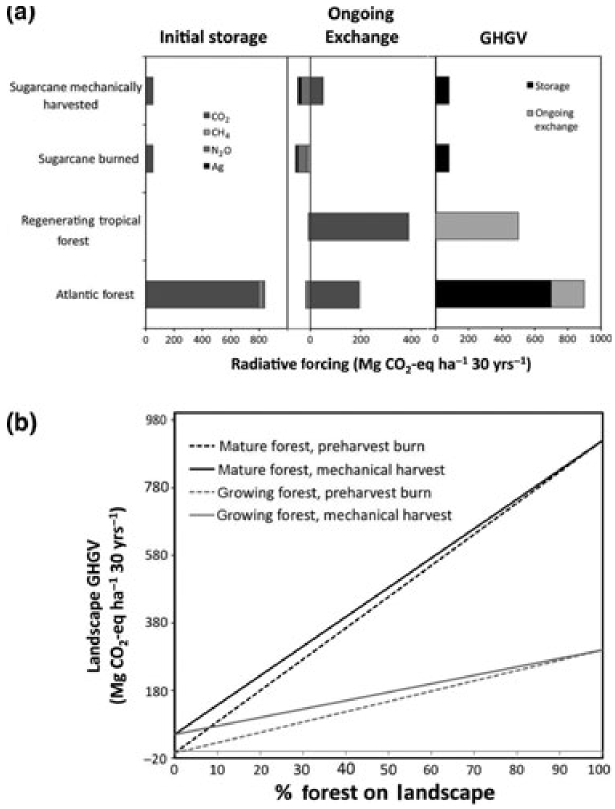

Fig. 1 Greenhouse gas mitigation benefits, quantified using the greenhouse gas value metric (*GHGV*; Anderson-Teixeira & DeLucia, 2011), of sugarcane crops and forests (a) individually and (b) in combination on a landscape. (a) Contributions to *GHGV* from storage of organic material (the clearing of which would release GHGs) and displaced ongoing annual GHG exchange (including '*Ag*.'- emissions from farm machinery and fertilizer production). These are combined to yield *GHGV*, which is calculated over a 30-year time frame. (b) *GHGV*s of sugarcane landscapes with varying amounts of forest cover. Shown are analyses for mature Atlantic Forest and regenerating forests in combination with sugarcane that is burned prior to hand harvesting and that which is harvested mechanically. *GHGV*s for forests and sugarcane were calculated using the methodology of Anderson-Teixeira & DeLucia (2011). Relevant data were obtained from the following sources: sugarcane- Ball-Coelho *et al.*, 1992; Macedo, 1998; Feller, 2001; de Campos, 2003; Cerri *et al.*, 2007; Macedo *et al.*, 2008; Smeets *et al.*, 2009; Lisboa *et al.*, 2011; Atlantic Forest aboveground biomass- Tiepolo *et al.* (2002), as cited in Vieira *et al.* (2008); pan-tropical averages for other forest characteristics- Anderson-Teixeira & DeLucia (2011).

and minimize transportation costs while providing the benefits discussed above. Finally, care must be taken to ensure that increased forest cover on existing sugarcane landscapes does not indirectly motivate sugarcane expansion into existing native forest regions.

Development of agricultural landscapes containing mixes of sugarcane and forests is both feasible and beneficial in terms of ecosystem services. The technology to efficiently recover biodiversity in the Atlantic Forest already exists (Rodrigues *et al.*, 2009). Moreover, the feasibility of planting sugarcane in conjunction with forest on a mixed landscape has already been demonstrated (Pinto *et al.*, 2003, 2005a,b). Increasing forest cover on sugarcane landscapes would greatly enhance the ecosystem services associated with sugarcane production (Fig. 1) and the overall environmental sustainability of sugarcane ethanol production.

Conclusions

The strategy proposed in this paper of (i) improving the scientific understanding of the physiology and molecular biology of sugarcane in order to enhance its use for bioenergy production; (ii) developing cellulosic ethanol technologies, and (iii) improving scientific knowledge about agronomy and ecology of sugarcane and applying it to decrease impact of sugarcane production on the environment is collectively termed the 'midway' strategy (Buckeridge, 2007). The 'midway' strategy consists of continuing to form a strong scientific basis for the development of sustainable and socially responsible ethanol production through the combined efforts of improvement in germplasm, physiological understanding, production processes, and informed ecosystem management.

In order to remain one of the world leaders in the science, technology, and production of sustainable bioenergy in the form of bioethanol, Brazil will need to invest in basic research capable of improving industry practices in the near future. There are currently a few research programs focused on this issue, and as a result of Brazil's current investiment in science and technology, a mature bioenergy industry with improved and highly sustainable first generation and adapted second generation bioethanol production is expected to emerge within the next 10–20 years. Such a system is expected to be much more efficient and to significantly increase bioethanol production, with consequent economical and environmental benefits for Brazil and the world. In order to guide and optimize this expansion, and to plan for longer term targets (20 years ahead), appropriate science and technology research needs to receive attention and investment now. These targets require daring attitudes and new ideas, but at the same time the goals must be connected with current targets so that the science and technology of the near future will serve as a basis for the next phases.

In order to realize the midway strategy proposed in this work, three main targets for the next 20 years should be pursued. The first target is the production of varieties, through a combination of classical genetics and biotechnology transformations, capable of producing pretreated biomass already adequate for industrial processing. This will require considerably enhanced scientific knwoledge regarding some key questions: (i) how is carbon flux controlled within the plant?; (ii) how are cell walls synthesized and degraded *in vivo*?; (iii) how can genetic transformation of feedstock be stabilized to keep these features for several generations? (iv) when they are stable, can sugarcane be used as 'biochemical factories', producing useful substances that can contribute to the route of the biorefinary? Concurrently, the industry of the future will have to adapt to the modified feedstocks by designing milder pretreatments and complementary hydrolysis processes.

Second, these 20-year goals will provide completely different feedstock features, and agriculture must adapt to these. The sugarcane varieties of the future will require less water and less fertilizer. They may have completely different physical properties such as higher proportion of fibers, which will significantly affect the harvesting process. Harvesting will likely be dominated by precision agriculture techniques, with very different plant distributions and growth characteristics. Considerably enhanced understanding of the physiology of sugarcane, together with genetic modifications, is expected to accelerate the production of modified sugarcane. This will require that agriculture adapts much faster, and it should therefore be constantly prepared to receive and implement new technologies. The forest code of Brazil, which is currently being revised, will have to comply with the needs of the future, providing the protection of the forest while its sustainable use is studied and the interest of industry in sustainability hopefully rises. Here, the role of communication and education will be crucial for the bioenergy producing system to become much more flexible in order to keep pace with envisioned future technology. Thus, as industry and agriculture technologies are improved, information will have to flow quickly and efficiently in order to make scientific and technological innovations a reality.

If the midway strategy is used to increase forest patches amidst sugarcane crops, the issue of the interaction between the two ecosystem types will require improved understanding. At the same time, it will be important to explore ways in which biodiversity and ecosystem services associated with forest can add value to the forest-sugarcane system.

Acknowledgements

This work was supported by the Instituto Nacional de Ciência e Tecnologia do Bioetanol (INCT-Bioetanol, CNPq/FAPESP) and the Energy Biosciences Institute (EBI).

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