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Review Article

Climate Change and Sugarcane Production: Potential Impact and Mitigation Strategies

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Sugarcane (*Saccharum officinarum* L.) is an important crop for sugar and bioenergy worldwide. The increasing greenhouse gas emission and global warming during climate change result in the increased frequency and intensity of extreme weather events. Climate change is expected to have important consequences for sugarcane production in the world, especially in the developing countries because of relatively low adaptive capacity, high vulnerability to natural hazards, and poor forecasting systems and mitigating strategies. Sugarcane production may have been negatively affected and will continue to be considerably affected by increases in the frequency and intensity of extreme environmental conditions due to climate change. The degree of climate change impact on sugarcane is associated with geographic location and adaptive capacity. In this paper, we briefly reviewed sugarcane response to climate change events, sugarcane production in several different countries, and challenges for sugarcane production in climate change in order for us to better understand effects of climate change on sugarcane production and to propose strategies for mitigating the negative impacts of climate change and improving sugarcane production sustainability and profitability.

1. Introduction

A combination of long-term change in the weather patterns worldwide (i.e., global climate change), caused by natural processes and anthropogenic factors, may result in major environmental issues that have affected and will continuously affect agriculture. Atmospheric CO_2 concentration ([CO_2]) has increased by about 30% since the mid-18th century due to increases in combustion of fossil fuels, industrial processes, and deforestation [1]. Projections indicate that atmospheric [CO_2] would increase to about 550 ppm in a low emission scenario or could double (800 ppm) from current levels in a high emission scenario by the end of the 21st century. Global warming is directly associated with increasing atmospheric [CO_2] and other greenhouse gases (GHG). Global surface mean temperatures had increased from 0.55 to 0.67°C in the last century and are project to rise from 1.1 to 2.9°C (low emission) or 2.0 to 5.4°C (high emission) by 2100 relative to 1980–1999, depending on GHG emission level, region, and geographic location [2].

Increases in atmospheric [CO_2] and air temperature can be beneficial for some crops (especially C_3 plants) in some places [3, 4]. Climate variability and climate change are projected to result in changes in sea levels, rainfall pattern, and the frequency of extreme high- and low-temperature events, floods, droughts, and other abiotic stresses [5, 6] as well as tornados and hurricanes [7]. High temperatures accompanied by drought stress have been two of the major issues influencing agricultural production and economic impacts in many regions of the world. The challenges, faced by the agricultural sector under the climate change scenarios, are to provide food security for an increasing world population while protecting the environment and the functioning of its ecosystems [8]. For most countries that are highly dependent on rainfall with limited or no proper irrigation conditions and/or that have poor mitigation systems, these challenges may be amplified [9].

Agriculture is vulnerable to climate change through the direct effects of changing climate conditions (e.g., changes in temperature and/or precipitation), as well as through the indirect effects arising from changes in the severity of pest pressures, availability of pollination services, and performance of other ecosystem services that affect agricultural productivity. Reduction of crop productivity is universally predicted in most status reports on effects of climate change [10]. Climate change poses unprecedented challenges to agriculture because of the sensitivity of agricultural productivity and costs of improving growth environmental conditions. Adaptive action offers the potential to manage the effects of climate change by altering patterns of agricultural activity to capitalize on emerging opportunities while minimizing the costs associated with negative effects.

2. Sugarcane Response to Climate Change Events

Sugarcane is an important industrial crop used for sugar and bioenergy. It is one of the world's major C_4 crops that mainly grow in the tropic and subtropic regions. Weather and climate related events (i.e., growth environment of atmospheric [CO_2], temperature, precipitation, and other extreme weather) are the key factors for sugarcane production worldwide, especially in many developing countries. The potential negative impact of climate change, especially temperature and rainfall, on sugarcane production in Zimbabwe has been reviewed by Chandiposha [15]. The sugarcane and sugar yields have fluctuated with extreme climate events (drought and tropical cyclones) [7]. A record sugar production (516,529 tonnes) in Fiji in 1994 was recorded because of favorable weather, but sugar productions in 1997, 1998, and 2003 were 47, 50, and 43%, respectively, lower than that in 1994 due to drought environment [7].

By using crop simulation models, Marin at al. [16] reported that climate change improved sugarcane water use efficiency and cane yield in some areas of Brazil. They predicted that cane yield in 2050 could be 15–59% higher than that at the current average level. Studies have also indicated that elevated [CO_2] under controlled environment increased sugarcane photosynthesis, water use efficiency, biomass, and productivity [17–19]. Improved water use efficiency of sugarcane under elevated [CO_2] is mainly associated with the reduced stomatal conductance [17, 18]. Although these findings from the controlled environment are important for better understanding of physiological mechanisms of sugarcane plant response to elevated [CO_2], they may not completely reveal the interactions of [CO_2] and other climate factors under field conditions. The most significantly positive effect would be on reduced incidence of frost, which is a major limitation on production [20] in most regions, such as Louisiana of USA, where growing season is short. When realizing these benefits, however, we have to take serious consideration for long-term negative impact on nutrient levels, soil moisture, water availability, and other conditions. A negative effect of increased temperature may occur in the tropical regions where cool winters are required to slow plant growth and increase sucrose storage. Probably the most dramatic effect of climate change on sugarcane production in Australia would be from the increase in sea level [21]. A significant proportion of sugarcane is grown along coastal areas. Any increase in sea level would make these areas difficult to farm and a large increase in sea level would require large areas to be abandoned [20]. The same is true in South Florida, USA.

High temperature due to climate change in Northeastern Brazil will increase the evapotranspiration rates reducing the amount of water available in soils, making the planting of sugarcane increasingly difficult [22] and considerably increasing irrigation demand [23]. Knox et al. [24] assessed climate change impacts on sugarcane production in Swaziland using crop modeling and found a decreasing trend for future projections for cane yield unless irrigation was included in the model because of high demand of irrigation. In the South Caribbean, sugarcane yield may decrease by 20–40% under a doubled [CO_2] climate change scenario based on outputs of a crop model [25]. The decreased yield was mainly attributed to increased water deficit stress caused by the warmer climate. Although increases in atmospheric [CO_2] and air temperature may benefit sugarcane growth and biomass accumulation in some regions of the world based on studies in pots [17, 18] and under controlled conditions [19] or based on crop modeling prediction [16, 26], sugarcane production is highly vulnerable to climate change due to increased frequency and intensity of the extreme weather events, such as drought, heat, flooding, typhoon, and frost [7, 15, 24, 27–29].

Effects of drought due to climate change on sugarcane growth and development depend on plant growth stage, the degree of water deficit stress, and duration of the stress. In general, drought in early and mid growth stages mainly reduces cane yield leading to low sucrose yield. Moderate drought in late growth stage can improve sucrose content in stalks. Drought is the most important stress factor for sugarcane production in China, a country ranked the top third in sugarcane production in the world, because more than 80% of sugarcane grows under rainfed conditions [30]. Drought in 2003/2004 in Guangxi, China, resulted in an 18% decrease in cane yield [27]. Sugarcane production was recorded high in 2007/08 in Guangxi because of the ideal distribution of rainfall and other favorable growth environment conditions. Cane yield, cane production, and sugar production were 83.8 t ha^{-1}, 77.1 Mt, and 9.41 Mt, respectively. However, a long duration of extremely low temperature and rainy weather in the region from January to February 2008 and the freeze temperatures caused severe damage of most sugarcane. In December 2009, the extreme freeze temperatures (-4 to -6°C) occurred again and drought in the 2010 early growing season (January–June) accompanied with severe freeze temperature in December resulted in considerable reduction in sugarcane production. Cane yield, cane production, and sugar production in 2010/11 dropped to 56.3 t ha^{-1}, 55.7 Mt, and 6.75 Mt, respectively [30, 31]. Similarly, drought conditions in 1983, 1997, 1998, and 2003 and the 1997 tropic cyclones in Fuji led to big decline (16–46%) in sugarcane production, compared to production in record years [7, 13, 14]. Water logging is also a widespread phenomenon that drastically reduces the growth and survival of sugarcane and the water logging stress led to 18–64% reduction in cane yield [32], depending on duration of water logging, plant growth stage, and cultivars [32, 33].

A shift in temperature due to climate change will have an effect on some of diseases, insects, and weeds in sugarcane production [15]. For example, Matthieson [34] reported that the incidence of smut disease [caused by *Sporisorium scitamineum* (Syd.)] is likely to increase due to high temperatures. The prolific dry weather exacerbates the symptoms of ratoon stunting disease. It is difficult to predict the effect of climate change on sugarcane rust diseases, but severe storms and hurricane can spread leaf scald, caused by *Xanthomonas albilineans* [35]. The more extreme weather events due to climate change have caused more overwintering pests (weeds and insects), more disease pathogens, and more input costs for reducing these risks to maintain a certain level of sugarcane production. For instance, sugarcane leaf brown rust (caused by *Puccinia melanocephala* Syd. & P. Syd.) and orange rust [caused by *P. kuehnii* (W. Krüger) E. J. Butler] diseases, especially orange rust, are big challenges for sugarcane production in Florida, USA [36–38]. Severity of rusts is associated with winter temperature and relative humidity in the region. Sugarcane orange rust in 2012 and 2013 in South Florida was the most severe since it was first found in 2007 [39] due to favorable climate conditions of warmer winter and high humidity for the rust spores surviving and fast development [38]. Growers used fungicides to control the negative effects of rusts on yields, but the cost of three split applications of fungicides (at a hectarage level) during a growing season was equivalent to 3 tonnes (Mg) of cane yield lost per hectare. The economic impact just for controlling orange rust in South Florida was approximately $63 million in 2013 based on the estimate of the Florida sugarcane industry.

The adaptation of farming systems to climate change in sugarcane production requires taking advantage of the potential benefits and minimizing potential adverse impacts on crop production. Therefore, a better understanding of the functions of these climate/weather factors and their impacts on sugarcane production can help manipulate plants to meet human needs and formulate adaptation or mitigation strategies. In the following parts of this paper, we attempt to briefly review sugarcane production in several different countries, such as Brazil, India, China, Thailand, Pakistan, and USA (developing and developed countries), to better understand effects of climate change on sugarcane production and to propose strategies for mitigating the negative impacts of climate change and improving sugarcane production sustainability and profitability.

3. Sugarcane Production in Top 10 Countries

The top 10 sugarcane production countries in the world in 2013 were Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Indonesia, Philippines, and USA and their cane productions (million Mg of cane) accounted for 34.1, 15.8, 5.8, 4.6, 2.9, 2.8, 1.6, 1.6, 1.5, and 1.3% (a total of 72%) of the world total cane production, respectively (Table 1). Cane yields (Mg ha^{-1}) in these countries ranked 29th, 40th, 39th, 26th, 51st, 25th, 19th, 31st, 37th, and 27th, respectively, in the 103 sugarcane production countries [13, 14]. In last 41 years, sugarcane production was linearly increased with years from 1973 to 2013 in all the top seven sugarcane production countries. Both sugarcane area and cane yield contributed to the increases in cane production, but increased area was a dominant contributor compared with cane yield except for Pakistan where increases in sugarcane hectarage and cane yield had similar proportion. Hectarage in Brazil, India, China, Thailand, Pakistan, Mexico, and Colombia increased by 500, 94, 237, 286, 57, 52, and 61%, respectively, and cane yields increased by 60, 38, 59, 70, 58, 11, and 24%, respectively, in last 41 years (1973–2013) based on linear regression. In the same period of years, sugarcane hectarage in USA increased only 31% and yield had no big change or slightly decreased (7.0%) (Table 2).

Table 1: The world top 10 sugarcane production countries in 2013 for their cane production, hectarage, and cane yield as well as their ranks in 103 sugarcane production countries.

Country	Production		Area		Yield	
	Million Mg	Rank	×1000 ha	Rank	Mg ha^{-1}	Rank
Brazil	739.27	1	9835.2	1	75.17	29
India	341.20	2	5060.0	2	67.43	40
China	126.14	3	1827.3	3	69.03	39
Thailand	100.10	4	1321.6	4	75.74	26
Pakistan	63.75	5	1128.8	5	56.48	51
Mexico	61.18	6	782.8	6	78.16	25
Colombia	34.88	7	405.7	9	85.95	19
Indonesia	33.70	8	450.0	7	74.89	31
Philippines	32.00	9	435.4	8	73.49	37
USA	27.91	10	368.6	11	75.71	27
World total	2165.23		26522.7		81.64	

Source: FAO of the United Nations, FAOSTAT, and Factfish [13, 14].

Additionally, cane yield was lower and the yield variation (CV) across years was much greater in most developing countries than that in USA. Averaged across 41 years from 1973 to 2013, mean cane yields in Brazil, India, China, Thailand, and Pakistan were 17.8, 21.0, 25.1, 31.7, and 44.1% lower, respectively, than that in USA (Table 2). Coefficient of variation (CV) values for cane yields across years in these five countries ranged from 11.5 to 20.4% compared to a CV value of 5.7% in USA (Table 2). When plotting sugarcane hectarage and yield against year, neither hectarage nor yield in the top five sugarcane production countries leveled off and the slope (indicating cane yield increasing rate) of the linear regression in Table 2 ranged from 0.49 (India) to 0.75 (Brazil) Mg ha^{-1} yr^{-1}. Although impact of climate change on sugarcane production depends on geographic location and on degree of adaptation, cane yields in most developing countries still tend to increase by improved cultivars and management practices. Therefore, increases in both sugarcane area and cane yield are still feasible in these countries in current environment. To consider increasing population and land limitation, improving sugarcane yields in future is more

Table 2: Maximum, minimum, and mean cane yields and coefficient of variation (CV) across last 41 years (1973–2013) for the world top 10 sugarcane production countries. The slope and r^2 values of linear regression cane yield and year for each country are listed in the table†.

Country	Maximum (Mg ha^{-1})	Minimum (Mg ha^{-1})	Mean (Mg ha^{-1})	CV (%)	Slope (Mg ha^{-1} yr^{-1})	r^2
Brazil	80.26	46.48	64.92	14.33	0.75	0.93
India	76.53	49.11	62.41	11.48	0.49	0.68
China	74.93	39.18	59.16	15.98	0.67	0.73
Thailand	76.20	30.14	53.93	20.42	0.70	0.58
Pakistan	57.23	31.57	44.19	15.48	0.50	0.76
Mexico	78.16	62.68	71.11	6.00	0.22	0.40
Colombia	101.81	57.23	84.87	10.68	0.45	0.36
Indonesia	149.02	55.17	84.08	26.57	−1.60	0.73
Philippines	96.52	58.59	74.27	11.94	0.25	0.12
USA	89.98	69.90	78.99	5.71	−0.14	0.14
World total	71.77	53.76	62.49	8.68	0.45	0.95

†Data source: FAO of the United Nations (FAOSTAT) and Factfish [13, 14].

important compared to hectarage for sugarcane production, especially in most developing countries.

4. Challenges for Sugarcane Production

In general, great variation in sugarcane yields exists in most developing countries across years (Table 2) and regions with varying rainfall and temperature due to low adaptive capacity, high vulnerability to natural hazards, and poor forecasting system and mitigating strategies [7]. High inputs and high costs of the production and low cane price are also very common in these developing countries, which results in low profits for sugarcane growers. For instance, sugarcane growers in major production areas (Guangxi, Yunnan, Guangdong, and Hainan) in China have planted some more profitable crops because of the financial considerations [11]. Sugarcane hectarage in Guangxi, the largest cane producing province, is expected to drop 6% in 2014/15 as farmers grow the low-labor input and fast-growing tree species for industrial use according to the Provincial Sugar Industry Bureau. Cane hectarage in Hainan is estimated to decline 11% in 2014/15 due to low profits according to provincial statistics. In addition to low prices, high labor costs have also contributed to a major part of low profitability. More than half of sugarcane hectarage is located in hilly areas where mechanized operation is unavailable and the use of hand labor for planting, field management, and harvesting considerably increases the input of labors. As the cost of labor continues to rise ($20/Mg cane), which accounts for approximately 27% of cane price ($71/Mg) in 2013/14, grower's profit from sugarcane was impacted considerably (Figure 1). Therefore, low prices of cane and high labor costs caused a great drop in net income for growers in 2013/14 [11]. Reducing production costs by introduction and development of creative technologies and expanding use of sugarcane products not only for sugar but also for ethanol, cellulosic biofuel, and other coproducts will improve profits under the current and future climate conditions.

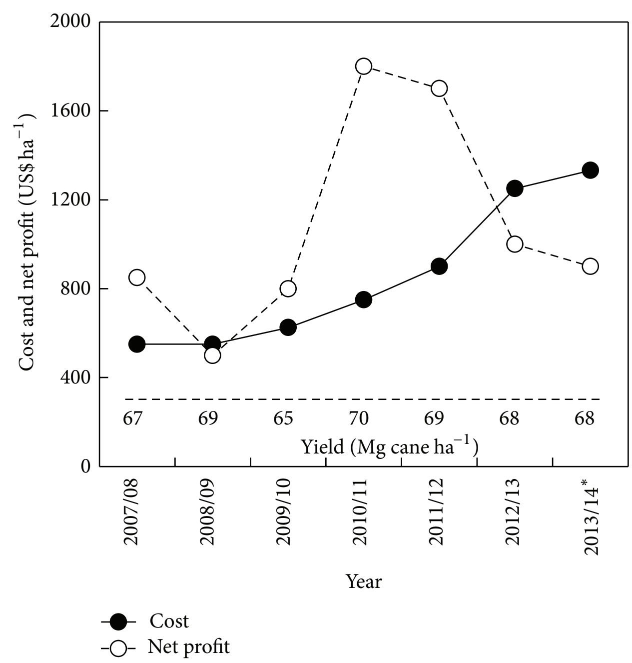

Figure 1: Average labor cost, net profit, and cane yield in major sugarcane production regions in China from 2007 to 2014. 2013/14* based on postestimate. Data are adopted from Anderson-Sprecher and Jiang [11].

When assessing agriculture and crop production systems as well as climate change and its negative impact on crop production, many economic, environmental, and social issues have to be thoroughly considered, such as how to (1) balance short-term and long-term goals; (2) increase productivity, profitability, and sustainability; (3) introduce new technologies and transfer them to growers; (4) meet environmental regulations; (5) deal with contradictions between climate change and crop production; and (6) balance competition of

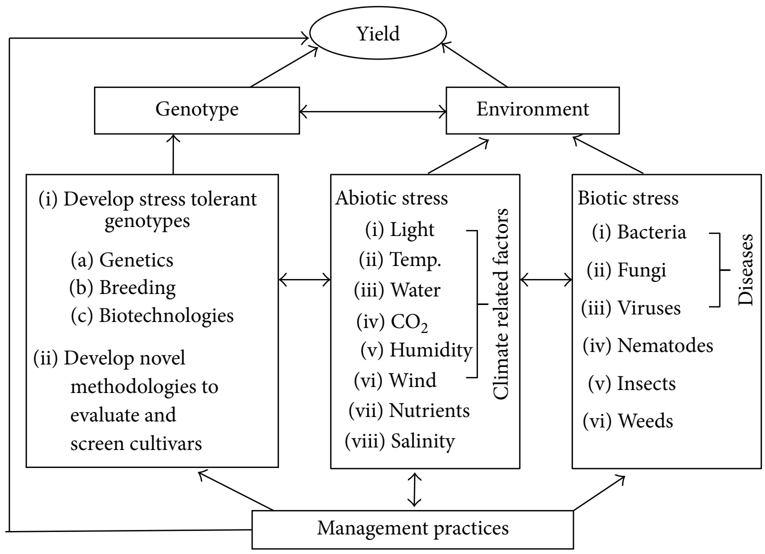

Figure 2: A flow chart to demonstrate major factors (genotype, environment, and management practices) influencing sugarcane yield as well as their interactions.

food and energy in resources. Certainly, sugarcane production systems are also challenged by these specific issues.

5. Mitigating Impact of Stress Environment and Sustaining Sugarcane Production

Although climate change increases the frequency and intensity of extreme weather events and uncertainty and vulnerability of adverse effects on agriculture [2, 6, 7, 9, 26, 29], the world sugarcane production was tripled in last 41 years [13, 14] because of increase in demand. The increased cane production was associated with increases in both hectarage and cane yield in most developing countries as described above. Much more efforts are needed to focus on increasing yield and improving profits under the current conditions and in the future climate change. Sugarcane yield relies on crop varieties (genotypes), biotic and abiotic growth environments (i.e., insects, diseases, weeds, and other climate related factors), and management practices (Figure 2).

Some mitigation and adaptation strategies for climate change in sugarcane production in Zimbabwe have recently been proposed [15] and these mitigation strategies included planting drought tolerant varieties, investing irrigation infrastructure, improving irrigation efficiency and drainage systems, and improving cultural and management practices. Based on long-term data collected in South Africa, Deressa et al. [40] suggested that adaptation strategies should focus special attention on technologies and management regimes that will enhance sugarcane tolerance to warmer temperatures during winter and especially the harvesting phases. Thus, development of the stress tolerant and high-yielding sugarcane cultivars is one of the important strategies in adaptation of climate change (Figure 2). Sugarcane breeders and other scientists can develop computer data base to design hybridization (within or between species) for special requirement in the breeding programs, use growth and physiological traits to screen elite clones for resistance/tolerance to biotic and abiotic stresses [41], and use tissue culture, molecular biology, and gene transformation technologies to improve breeding and selection efficiencies. Studies have shown that some genotypes/cultivars are better than others in tolerance to water deficit [41–43] and low temperature [13] stresses, in radiation use efficiency [44], and in nutrient use efficiency [45, 46].

Using 33-year data of sugarcane yields in Florida to estimate the contribution of a breeding program to sugarcane production, Edmé et al. [47] found that sucrose content, cane tonnage, and sugar yield of the Florida commercial sugarcane cultivars linearly increased by 26.0, 15.5, and 47.0%, respectively, from 1968 to 2000. They found that the increases in yield components mainly occurred on the Florida organic soils. Underscoring the critical need for cultivar development for the Florida sugarcane industry, about 69% of the sugar yield gain came from genetic improvement attributable to the Canal Point (CP) cultivar development program. Recently, we planted 12 CP-sugarcane cultivars/genotypes that have a wide range of released years (from 1980 to 2013) on sand soils at two locations in Florida in 2011. The 3-year results of this study indicated that sucrose yield linearly and positively related to the cultivar-released year ($r = 0.77^{**}$). The increased sucrose yield on the Florida sand soils for the latest released cultivars was mainly associated with cane tonnage ($r = 0.73^{**}$) rather than commercial recoverable sucrose ($r = 0.17$) (unpublished data, Figure 3). Based on pot and field studies with intensive measurements of physiological, growth, and yield traits, we also found that some sugarcane genotypes are more tolerant to stress environment than others [43, 46, 48]. Therefore, development of new sugarcane cultivars that can contribute to adaptation to climate change (especially for elevated CO_2 and temperature) by discovering and introducing desirable genes for agronomic trait development [49] and using basic breeding [50], physiological screening [41, 43], and new

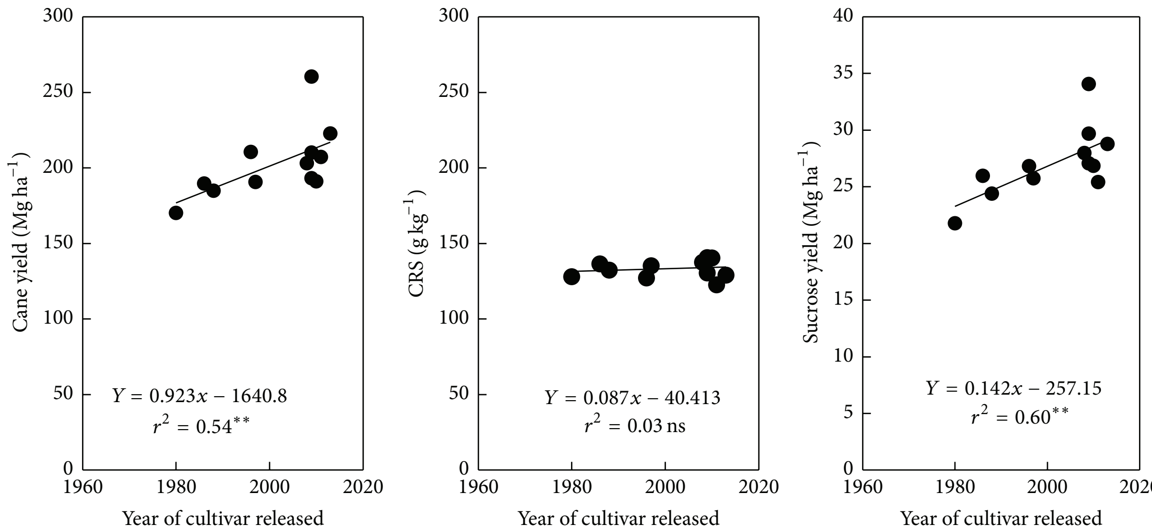

Figure 3: Trends of cane yield, commercial recoverable sucrose (CRS), and sucrose yield for 12 sugarcane cultivars or genotypes grown on sand soils at two locations in Florida. These cultivars had a wide range of released years from 1980 to 2013.

technologies of molecular biology [51] can mitigate the negative effect of climate change and improve sugarcane yields, productivity, and sustainability.

Using technologies of molecular biology and gene transformation to develop genetically modified (GM) sugarcane varieties [52–54], such as herbicide glyphosate resistance, drought tolerance, high sugar content, and disease resistance, may be one of the important ways to mitigate negative impacts of environmental stresses due to climate change. To address some of the potential concerns regarding safety of the GM sugarcane products, Joyce et al. [54] compared the GM sugarcane with non-GM control for product quality. They found that sugar crystallized from GM sugarcane plants did not contain residual DNA or proteins of introduced transgenes. The finding will improve the public perceptions surrounding GM sugar and its potential future incorporation within commercial sugarcane production.

Diversity of cropping systems, crops, and cultivars within a crop is also important for mitigating negative effect of climate change, biotic and abiotic stresses, or other uncertain extreme climate events because there are considerable differences among plant species, cultivars, and cropping systems in tolerance to stresses. Sugarcane cultivar Q124 in Queensland, Australia, in 2000 accounted for 45% of the crop, but a new race of orange rust pathogen devastated this high-performing cultivar and caused the industry Aus$ 150–210 million in yield losses [55, 56]. In a region, therefore, sugarcane variety diversity is also imperative for reducing risk of extreme climate factors, for mitigating negative effects of stress environment, and for improving sustainability of sugarcane production. Sugarcane cultivars with a wide range of maturity can buffer the harvest time and reduce the pressure of labor shortage and milling capacity, for instance, a total of 172,100 ha of sugarcane in the 2012-2013 harvest season in Florida with 12 major cultivars [12]. The fractions of these cultivars in Florida are listed in Figure 4. It is suggested that each of the leading

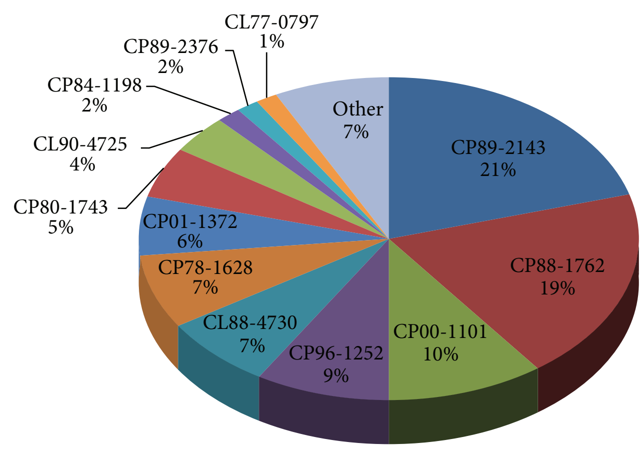

Figure 4: Commercial sugarcane cultivars and their % of total hectarage in the 2012-2013 harvest season in Florida. Total area = 172,118 ha. Data are adopted from Rice et al. [12].

sugarcane cultivars in a region may not be over 25% of total hectarage in order to mitigate negative effects of the extreme climate events on sugarcane production and to reduce risk of yield losses by some unexpected insects and diseases.

Severity of most sugarcane diseases is associated with the climate related factors. Sugarcane orange rust disease in Florida was much severer in the 2012 and 2013 growing seasons than other years due to warmer winter and higher humidity [37]. Sugarcane smut disease was severer on sandy soils than on organic soils because of high temperature and relative dry conditions. In addition to development of disease resistant cultivars by breeding and variety development programs, integration of the best management practices (BMPs) for pest control and for increases in water and nutrient use efficiencies is also crucial for the climate change adaptation and sugarcane yield improvement.

These BMPs include carbon sequestration, soil tillage, irrigation methods and scheduling, drainage, nutrient monitoring, and fertilizer applications. All of these are associated with geographic locations and long-term climate change and have been reviewed in detail recently [15, 57]. Biggs et al. [58] found that the frequency of years with very high N losses is predicted to increase under projected climate change and improved farming practices can more effectively limit N losses than traditional practices. The use of ripeners and withholding irrigation prior to harvest can improve sucrose content of stalks. Additionally, integration of seasonal climate forecasting with proper management strategies has potential to benefit sugarcane production in many areas [59]. The details of cultivar development and management strategies for sugarcane production in China have been proposed [27, 30, 60]. Applications of plant growth regulators can be useful for improving plant tolerance to some specific stresses and for sugar yield enhancement. Studies have indicated that using low concentration of ethylene-producing substances such as ethephon to treat seed canes or yang plants at early growth stage can improve the drought tolerance and mitigate other abiotic stresses of sugarcane plants [61, 62]. Foliar application of low concentration of ethephon alleviated the injury of cell membrane caused by water deficit stress, maintained relatively lower osmotic rates of electrolytes and soluble sugar, increased the proline content and water potential in the leaf tissues, promoted the activities of cell protective enzymes (such as peroxidase, catalase, and polyphenol oxidase), and improved the gas exchange characteristics. The physiological and biochemical base of plant growth regulator applications and their beneficial effects on sugarcane growth under drought conditions have been reported in detail by Botha et al. [61] and Li [62]. The foliar application of ethephon in a low concentration may be used as a management practice to partly mitigate drought effect on sugarcane growth and yields.

6. Sugarcane Impact on Local Climate

In a region, changes in farming systems and crop combinations may directly or indirectly affect local climate factors. Residue burning before or after sugarcane harvest is a common management practice of sugarcane production in many countries. Greenhouse gas emission in sugarcane production is the major concern. A recent research [63] indicated that approximate 2.4 tonnes of CO_2 equivalent ha^{-1} was released to the atmosphere by sugarcane crop. The major contributors of the released CO_2 from sugarcane were residue burning (44%), the utilization of synthetic fertilizers (20%), and fossil fuel combustion (18%) [63]. Therefore, improving green harvest can increase soil organic carbon and reduce CO_2 emission from sugarcane production.

Georgescu et al. [64] investigated the direct climate effect of perennial bioenergy crops in the United States. Their results demonstrated that a thorough evaluation of costs and benefits of bioenergy-related land-use change must include potential impacts on the surface energy and water balance to comprehensively address important concerns for local, regional, and global climate change. Expansion of sugarcane can relatively increase carbon fixation and carbon sequestration because of its C_4 carbon fixation characteristics. A recent study [65] in Brazil, using maps and data from hundreds of satellite images, has revealed that, on a regional basis for clear-sky daytime conditions, conversion of natural vegetation to a crop/pasture warms the region by an average of 1.55 (1.45–1.65)°C, but subsequent conversion of the crop/pasture to sugarcane cools the region by an average of 0.93 (0.78–1.07)°C, resulting in a mean net increase of 0.6°C. They concluded that expanding sugarcane into existing crop and pasture land has a direct local cooling effect that reinforces the indirect climate benefits of this land-use option. Therefore, sugarcane may be better than other field crops for environmental protection in increasing atmospheric [CO_2] and surface temperature. Further research is required to reveal the mechanisms of the direct local cooling effect of sugarcane.

7. Summary and Future Perspectives

Clearly, sugarcane production has been and will continue to be directly or indirectly affected by changes in climate conditions. The most significant challenges for sugarcane production are increases in frequency and intensity of extreme weather events, especially drought during climate change. Existing adaptation strategies can help offset many but not all effects in the future. The negative effects of climate change on sugarcane production are very likely to worsen after 2050, especially if greenhouse gas emissions still remain high. Therefore, agricultural scientists and decision makers need to work closely to mitigate the potential negative effects of climate change on agriculture and to improve sugarcane yields by multidisciplinary approaches, such as consistently developing new sugarcane cultivars using breeding and molecular biology, refining best management practices, improving new technology transfer, and increasing productivity and profitability. Improving the resilience of sugarcane production systems to climate change requires protection of the natural resource (especially water and soil) for sustainability. Expanding use of sugarcane products for sugar, ethanol, cellulosic biofuel, and other coproducts can further improve profits.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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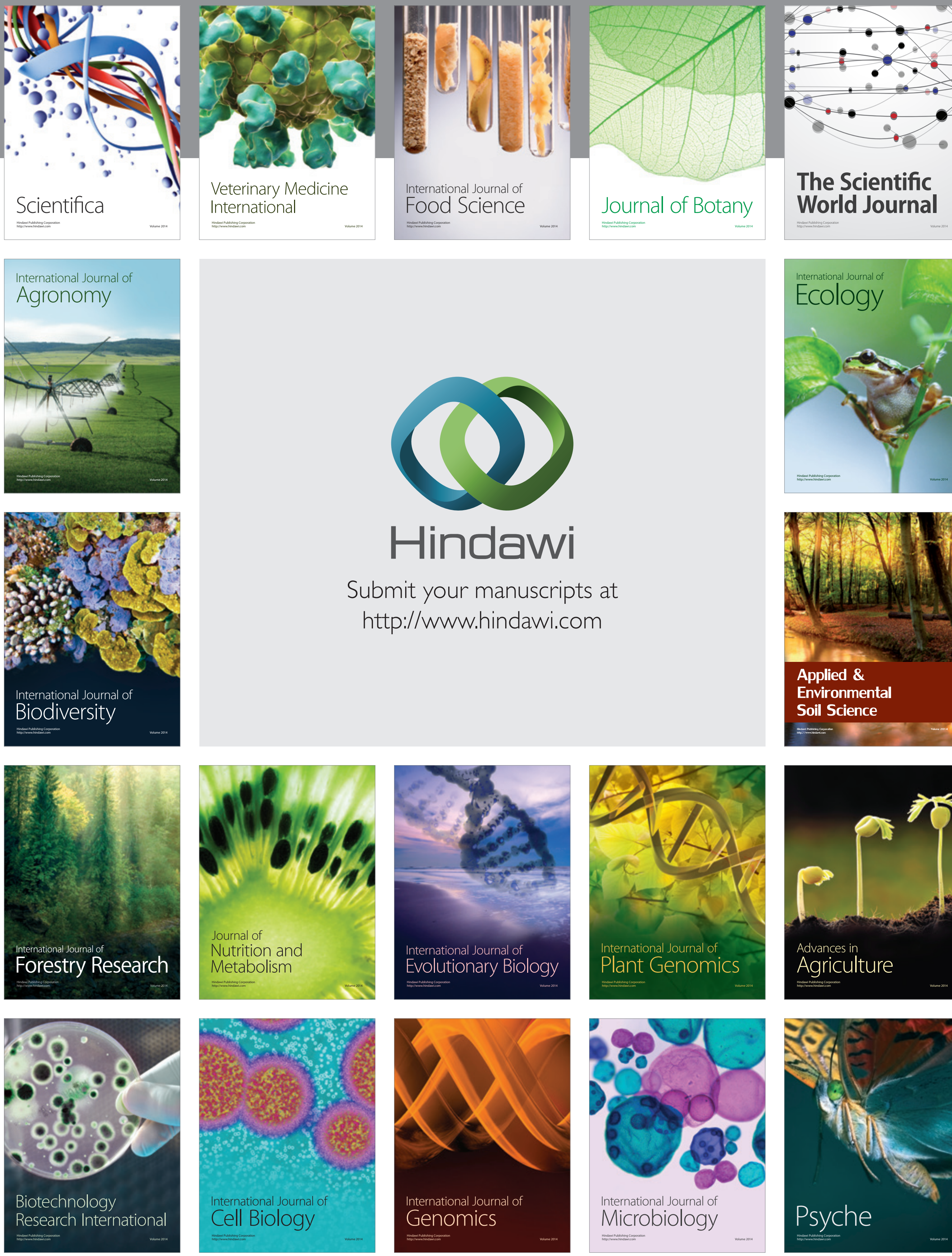
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