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REVIEW

CHALLENGES AND OPPORTUNITIES IN SUGARCANE CULTIVATION UNDER CLIMATE CHANGE SCENARIO

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Abstract

Climate change is a global phenomenon with pronounced impact on agricultural production mainly due to elevated atmospheric CO_2 concentration, global warming and erratic rainfall patterns. The impact is likely to aggravate in the coming decades as the scope for complete replacement of fossil fuels in the near future is uncertain. Agriculture, being climate dependent, will have to face both the positive and negative impacts of it. Long term observations and future predictions establish that climate change is really happening and there is a compelling need to find short and long term solutions to mitigate its negative influence on crop production. Voluminous data generated through research and real time observations by various organizations and the IPCC present both positive and negative impacts of elevated atmospheric CO_2 concentration, temperature, erratic rainfall, etc. on crop growth and productivity. Being a C4 plant of long duration, the impact of climate change on sugarcane needs to be studied to sustain sugar and energy production. The results of limited *in-vitro* studies and simulation models on the impact of climate change on sugarcane are reviewed in this article. Though it was predicted that the already CO_2 saturated photosynthesis of this C4 plant may not respond positively to elevated atmospheric CO_2 concentration, the results on the stomatal regulation of transpiration and the resulting increase in water use efficiency give hope to develop varieties that would adapt the climate change. Since regional variations in the response of sugarcane to elevated CO_2 and temperature were observed, research should focus on developing region specific mitigation and adaptation strategies. Many predicted negative impacts like climate induced biotic and abiotic stresses, deterioration of soil and water resources, shift in weed species, pest and disease patterns, cane quality deterioration, etc. ring the alarm bells and attract immediate research initiatives for studying the impacts as well as for developing strategies to overcome them. Breeding climate resilient sugarcane varieties which are high CO_2 concentration responsive, high water and nutrient use efficient, stress tolerant, adaptive to symbiotic and free living beneficial microbes, aiding carbon sequestration through high underground and above ground biomass, rhizo-deposition, resistant to pests to and diseases, etc. should be given priority. Technologies to reduce the greenhouse gas (GHG) emissions through residue recycling, soil and water conservation, improving the fertilizer use efficiency are already available and these require large scale adoption.

Organic manuring and crop residue incorporation are time tested agricultural practices and sugarcane crop offers ample quantity of residues for composting and recycling. Minimizing soil tillage helps to reduce mineralization of soil organic matter and aids in soil carbon sequestration. Biochar from sugarcane trash and bagasse are potential sources for not only carbon sequestration but also as amendments to improve soil health, nutrient use efficiency and water use efficiency. Sugarcane produces plenty of phytolith carbon, which are silica structures called plant stones with embedded carbon molecules called PhytOC, that persists in soil for several years and offers hope for soil carbon sequestration and an opportunity to include this trait in varietal development. Though biofuel sector is picking up momentum, boosting the sugarcane based biofuel production and energy conservation measures in sugar and allied industries will augment our efforts in mitigating the vagaries of climate change.

Key words: Climate change, sugarcane, adaptation, mitigation, soil carbon sequestration, biochar, phytolith, plant stones, PhytOC, biofuel

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Introduction

Climate change is a state of the climate that can be identified by changes in the mean and/or the variability of its properties that persists for an extended period, typically decades or longer. It is a global phenomenon with pronounced impact on agricultural production. In the context of environmental policy, the term climate change has become synonymous with enhanced atmospheric CO_2 concentration and global warming. Between 1970 and 2004, the concentration of greenhouse gases (GHGs), namely CO_2, CH_4, N_2O, hydro-fluoro-carbons, per-fluoro-carbons and sulphur-hexa-fluoride, which are responsible for global warming and climate change, has increased by 70%. Among the GHGs, CO_2 emission since 1750 has made the largest contribution to global warming. Methane is 21 times more potent and nitrous oxide is 310 times more potent than CO_2. The short lived CH_4 had increased by 150% between 1750 and 2011 and hence the impact of methane on climate was much higher. Fossil fuel emissions in the industrial era and large-scale modification of the landscape in the past several millennia have contributed about 90% and 10% to total CO_2 emissions (Ballantyne et al. 2012; Bala 2013). The pre-industrial era CO_2 in the atmosphere was 250 ppm, which rose to 383 ppm by 2007 and is rising at 2 ppm annually (IPCC 2007). The May 2013 issue of Nature reported that the hourly values of CO_2 concentrations at Mauna Loa, Hawaii, have already crossed the symbolic milestone of 400 ppm in April 2013 (Monastersky 2013). It is projected to reach 405 to 465 ppm by 2025, 445 to 640 ppm by 2050 and 720 to 1020 ppm by 2100 (IPCC, 2001, 2007). Based on the mass of the global atmosphere and molecular weights of dry air and CO_2, the mass of 1 ppm of CO_2 is approximately equivalent to 2 billion tonnes of C or 7.5 billion tonnes of CO_2 in the atmosphere (Bala 2013).

The IPCC's fourth assessment report projected that the global temperatures will rise between 1.8°C and 4.0°C by 2100 depending on emissions of GHGs and that global sea levels are likely to rise from anywhere between 180 mm and 590 mm (IPCC 2007). The IPCC report tabled in the UN Framework Convention on Climate Change, Warsaw, stated that the rate of warming during 1951 to 2012 was 0.12°C per decade but during the period from 1998 to 2012, it was only 0.05°C (Sethi 2013).

With a doubling of pre-industrial levels of CO_2 in the atmosphere, the General Circulation Model (GCM) by the United Kingdom Meteorological Office (UKMO) predicts a temperature increase of 16.2% (Dinar et al. 1998) in India. Agricultural activities are also responsible for the release of significant amounts of greenhouse gases (Dhillon and von Wuehlisch 2013). Agriculture directly contributes between 5.1 and 6.1 Pg CO_2 equivalent to global GHG emissions. These emissions are mainly in the form of methane (3.3 Pg CO_2-eq/yr) and nitrous oxide (2.8 Pg CO_2-eq/yr) whereas the net flux of CO_2 is very small (0.04 Pg CO_2-eq/yr). In the agricultural system, CO_2 is released largely from biomass burning, microbial decay and soil organic matter.

Reduction of crop productivity is universally predicted in most status reports on the effects of climate change (Lobell et al. 2008). The major hindrance to crop productivity in the near future was predicted to be abiotic stresses like drought, water logging, tropical cyclones, soil moisture deficit, salinity, alkalinity, increase in temperature, water stress, etc., leading to a rise in areas with high climatic risks (Dhillon and von Wuehlisch 2013). Trenberth et al. (2007) projected changes in the frequency of extreme high-temperature events, floods and droughts due to climate change and variability. Makino and Mae (1999) in their review on photosynthesis and plant growth at elevated CO_2 perused the related research results and concluded that short-term CO_2 enrichment stimulates the rate of photosynthesis and enhances plant mass but the long-term CO_2 enrichment reduces the initial stimulation of photosynthesis in many C_3 species and suppresses photosynthesis due to secondary responses related to either excess carbohydrate accumulation or decreased N. They have concluded that CO_2 enrichment is not a stress for plants and hence plants might have lacked the need to acclimate to elevating CO_2. The IPCC report indicated a probability of 10-40% loss in crop production in India and other countries of South Asia with increase in temperature by 2080-2100 and decrease in irrigation water (IPCC 2007). Under such climate change scenario, the research results on the impact of climate change on sugarcane, probable strategies to mitigate the impact of climate change and the technology options to reduce the emission of GHGs and enhance the soil carbon sequestration potential in sugarcane farming are reviewed in this article.

Impact of climate change on sugarcane

Sugarcane being an annual crop, the impact of climate change could manifest with great intensity. Different stages of crop growth like germination, tillering, grand growth and maturity phases are vulnerable to the impact of climate change which can adversely affect the overall productivity of the crop. However, the crop is highly resilient and the extensive genetic variability in terms of adaptation present in the varieties and germplasm offers scope for mitigating the effects of climate change through varietal approach.

Studies on the impact of climate change on sugarcane productivity have been conducted using simulation models and also using the modified environment chambers. Simulation models such as APSIM-Sugarcane (Australia) and CANEGRO (South Africa) are already available in the sugar industry for prediction of sugar and cane yield based on variables related to soil, water and temperature besides other environmental parameters. These models operate on (1) the effects of stress (water, temperature and N) on the partitioning of photosynthates to stored sucrose; (2) the response of different cultivars to stress and (3) differences between plant and ratoon crops with respect to Radiation Use Efficiency and Transpiration Efficiency (O'Leary 2000).

Sugarcane is a water demanding crop, necessitated by its long duration in the field and huge biomass production. As the requirement of water for the crop is large particularly during vegetative growth, water stress may reduce the productivity significantly. The most vulnerable regions of the world are the tropics, particularly the semi-arid regions where higher temperatures and increase in rainfall variability could have substantial negative impacts (Parry et al. 2004; Srivastava et al. 2010). The IPCC (2007) has projected that the rise in surface air temperature to the extent of 1.8-4.0°C together with very likely occurrence of frequent warm spells, heat waves and heavy rainfall, and a likely increase in the frequency of droughts together with the increase in the CO_2 concentration will influence sugarcane production in India.

It is generally believed that the effect of CO_2 fertilization may not result in any significant increase in the yield of C4 crops, as C4 photosynthesis is already CO_2 saturated (von Caemmerer and Furbank 2003). By using the C4 photosynthetic cycle to concentrate CO_2 at the Rubisco site to levels many fold higher than ambient CO_2, C4 plants are able to achieve a greater photosynthetic capacity than C3 plants at the current atmospheric CO_2, particularly at high growth temperatures (Matsuoka et al. 2001). Due to this, the photosynthesis is practically near to saturation at current atmospheric CO_2 and therefore C4 plants would not show significant growth responses to a rise in ambient CO_2 (Bowes 1993). However, there are also reports on the positive impact of elevated CO_2 levels on crop growth. Experiments conducted under elevated CO_2 conditions have conclusively pointed out that the elevated CO_2 stimulates carbon assimilation under drought conditions or in short-term water stress conditions due to an increase in water use efficiency via reduction in stomatal conductance (Ghannoum et al. 2000; Vu and Allen 2009a). Long et al. (2004) also reported a positive growth response to elevated CO_2 in C4 plants. Enhancement of CO_2 enrichment rate under elevated CO_2 conditions and up-regulation of the capacity of certain key photosynthetic enzymes and sucrose metabolism in young developing leaves was demonstrated by Vu et al. (2006). Sugarcane plants grown for three months at doubled CO_2 and high temperature combination accumulated more leaf area and leaf and stem biomass than plants grown at ambient CO_2 and near-ambient temperature conditions (Vu and Allen 2009a). An improvement in water use efficiency as a result of long-term exposure to elevated CO_2 would likely be more important than the increase in net CO_2 uptake per se in terms of plant growth and final yield (Chaves and Pereira 1992). The lower stomatal conductance reduces sap flow and increases xylem potential, leading to an improved plant water status (Owensby et al. 1997). Increased CO_2 will lead to significant reduction in crop transpiration and thereby evapotranspiration resulting in reduced water stress severity and increase in cane yield (Ziska and Bunce 1997; Vu et al. 2006; desouza et al. 2008; Vu and Allen 2009a). Enhancement in juice Brix at doubled CO_2 and high temperature combination has been reported by Vu and Allen (2009b). In addition, an improvement in leaf water use efficiency under doubled CO_2 and high temperature, as observed at various growth stages of the leaf (Vu et al. 2006), contributed to the increases in sugarcane biomass and sugar accumulation.

Temperature influences yield by regulating the rate of biomass accumulation through photosynthesis and the duration of growth (Vu et al. 1997; Fuhrer 2003). The optimum temperature for photosynthesis is higher in C4 plants as compared to C3 plants (Rosenberg et al. 1983; Taiz and Zeiger 1991). Optimum temperature for sprouting of sugarcane is 32-38°C and for optimum growth is 22-30°C. Minimum temperature for active growth is approximately 20°C. For ripening, however, relatively lower temperatures in the range of 20-10°C are desirable, since this has a noticeable influence on the reduction of vegetative growth rate. Any changes in temperature beyond this optimum are likely to affect the productivity.

Regional variations in sugarcane productivity in response to local climate change scenarios must be given due importance. Deressa et al. (2005) assessed the economic impacts of climate change on sugarcane in South Africa using a Ricardian approach. By combining critical damage point analyses with information on agro-climate variability, they showed that sugarcane production and revenue are more sensitive to increase in temperature and less sensitive to rainfall. The impact of an IPCC scenario of doubling CO_2 (which will lead to rise in temperature by 2ºC and precipitation by 7%) was negative on sugarcane production in all zones under both irrigation and dry land conditions. Sugarcane cultivation under irrigation does not provide an effective option for reducing climate change damages in South Africa. There were no sugarcane yield losses in southern Brazil for the climate projections analyzed, with gains ranging from 1% to 54%. Simulation studies using DSSAT/CANEGRO for Brazil revealed that cane yield responded positively to an increase in air temperature up to +6°C (11% higher than the baseline), decreasing thereafter (Marin et al. 2012). Increased temperatures caused large increase in potential evapotranspiration (7.8% for +3°C rise) and accelerated canopy development. This resulted in an increase in canopy photosynthesis and actual crop evapotranspiration (6.6% for +3°C) due to increased interception of radiation resulting in an increase in severity of water stress.

Biggs et al. (2012) found that sugarcane yields in Australia increased by 8% and 4% with weak climate change and moderate climate change, respectively, but were reduced by 10% with strong climate change. CO_2 fertilization increased the yields by 10 - 14% and the N loss was reduced due to CO_2 fertilization. Simulating climate change impacts for irrigated sugarcane production in Swaziland, Knox et al. (2010) found a decreasing trend for future projections for cane yield unless irrigation was included in the simulations. The simulated sugarcane production in Mauritius was found to decrease by 32-57% under GCM scenarios and by 3-81% under incremental scenarios (Appadu 1999). The reduction resulted mainly from lower water use efficiency and more than 20% rainfall was needed to offset a 2°C rise in temperature. It was further shown that for every 2^{o}C rise in temperature, sucrose yield will be reduced by about 32% (Lal 2011).

Manifestation of climate change has a different dimension in the Caribbean with increased frequency of tropical storms and floods, reduced fresh water supplies and rise in sea levels. Both very high rainfall and severe droughts can affect sugarcane production and more importantly, the sugar content (JISW 2006). Too much rain in the mature stage would damage the cane while lesser rainfalls at the initial stages can affect the growth of the young cane. Singh and El Maayar (1998), using GCM (CCC 11) outputs and high, medium, and low CO_2 emission scenarios coupled with a crop model to simulate crop yields, found that sugarcane yields may decrease by 20-40% under a doubled CO_2 climate change scenario in Trinidad and Tobago in the Southern Caribbean. The decrease in yields was attributed to increased moisture stress caused by the warmer climate.

Emerging scenario

Though there had been several studies in the past, the overall scenario with respect to sugarcane agriculture in relation to climate change remains speculative. Increased CO_2 levels may have negative or positive impacts on productivity as the studies indicate. With increased temperature and more sunshine hours the photosynthetic efficiency and productivity in cooler regions may improve, but can have adverse effect on sucrose accumulation. Decreased yield and sucrose accumulation are expected in areas where more number of days exhibit above 34ºC. Moisture stress during the formative phase of growth will affect germination and tillering leading to reduced stalk population and reduced initial stalk growth. On the contrary, under limited moisture stress during ripening period there could be an improvement in sucrose content in cane. Moisture stress usually coincides with the hot weather period and the situation gets aggravated due to higher evaporative demand and high direct effect of temperature on the crop. There could be risks of droughts or untimely floods, under the increased temperature regime depending on the locations. Flood-survived canes show remarkable improvement in Brix but with reduction in sucrose and increase in glucose. The effect of water logging may also be aggravated by the predisposing cultural environment like drought, lack of irrigation, and water-transmissible diseases like red-rot in the post-water logging phase caused by cyclones. Water logging leads to anaerobic conditions in soil which can adversely influence the function of roots and also induce flowering and ageing.

Besides the impact on sugarcane, elevated CO_2 regime may enhance competition from weeds, particularly dicots, as they are likely to flourish under such conditions. This will affect the productivity of the crop and increase the cost of production. The climate change scenario also forecasts more pests and diseases that can make the crop management more expensive. Climate change affects pathogen, host or the host-pathogen interaction (Coakley et al. 1999; Huang et al. 2005, 2006; Garrett et al. 2006). The change in climatic conditions will have an impact on the pathogen biology, thus influencing the virulence pattern and pathogen variability. New variants in pathogens may appear more frequently causing serious epidemics of diseases like red rot. Incidence of sugarcane smut has been reported to increase with rise in temperature. In the long run, a possible epidemic of smut is foreseen. Smut is a common disease in most of the African countries where the prevailing temperature is significantly high. Sugarcane diseases like wilt and yellow leaf diseases are more pronounced when the crop is exposed to diverse weather conditions like high temperature, water stress, etc. Hence incidence of wilt and YLD may increase due to temperature stress. Minor foliar diseases like rust and Pokkah Boeng are becoming major diseases consequent to changes in climatic conditions.

In a changed climatic scenario due to global warming, if the ambient temperature remains within the favourable range for pests, insect species will complete more generations thereby leading to larger populations than normal. A predominantly summer pest like shoot borer is likely to extend its activity beyond the month of May under spring planting in subtropical situation which is hitherto not the case. If such higher temperature is coupled with delayed rains leading to a drought-like situation, there can be a shift in the mode of shoot borer attack from shoots to internodes of grown-up canes. In a pest like top borer that follows a specific brood pattern, increase in temperature and delay in rains can negatively affect the development of third brood which is the most destructive phase, possibly reducing its damage. However, if the ambient temperature rises above the favourable ranges of different pests in the long-run, pest populations may be adversely affected. Areas that are not favourable for certain pests at present due to prevailing temperature may become favourable with a rise in temperature. Thus some of the tropical pests may become serious pests of sub tropics. This may be particularly true with internode borer. With an increase in temperature, there may be delayed onset and early suspension of hibernation. This would initiate early pest activity and extend the duration of damage of pests like top borer, root borer, Gurdaspur borer, Plassey borer, etc. that overwinter in the subtropics. The pests are also likely to complete one or two additional generations due to rapid development rates under elevated temperature. Some of the parasitoids used in biocontrol, which are sensitive to high temperatures like *Trichogramma* spp, may be adversely affected by rise in temperature.

Mitigating the impact of climate change

Mitigation of the impact of climate change will have multiple dimensions. The first and foremost will be to reduce the emission of greenhouse gases of anthropogenic origin. Reduction in the use of fossil fuels as also other major GHGs like methane and CFC is of primary importance. Use of alternate and non-polluting energy sources like solar energy, hydrogen fuel cells, wave energy, bio-ethanol and biodiesel, and cogeneration from biomass are some of the options available. Besides, improving the energy efficiency of the existing energy generating and consuming plants and machineries, and reducing the atmospheric CO_2 levels by carbon capturing and sequestration will moderate the global warming significantly. In addition, strategies have to be devised for mitigating the impact of climate change to sustain agricultural productivity on a long term basis. This will include development of CO_2 efficient, thermo-tolerant, waterlogging and flood tolerant, nutrient and water use efficient crop varieties to fit into the changing climate scenario. Management of soils to reduce CO_2, N_2O and methane emission, minimizing the carbon mineralization through reduced tillage, improving soil organic carbon content, improving water and nutrient use efficiency, etc. will have long term benefits in sustaining productivity of crops.

Mitigation of climate change impact in sugarcane agriculture

a. Breeding varieties to meet climate change challenges

Apart from breeding sugarcane varieties for conventional traits, consideration must be given for traits like high N use efficiency, good symbiosis ability, high CO_2 responsiveness, deep root system, carbon sequestration ability, phytolith production, etc. Sustainable sugarcane production systems necessarily involve low demands for inorganic N with mutualistic symbiosis for atmospheric N fixation. Diazotrophic endophytes that reside in xylem cells (*Glucoacetobacter diazotrophicus*) (Cavalcante and Dobereiner 1988) and rhizosphere

(*Azotobacter*, *Azospirillum*, *Beijerinckia*, *Derxia*, *Enterobacter* and *Erwinia*) (Thaweenut et al. 2011), partially supply the plant's N requirement, and minimize N fertilizer applications. Each kg of N saved is equivalent to 0.86 kg of C conserved in terms of fossil fuel burning (IPCC 1996). There are also indications that modern varieties can improve the N use efficiency through genetic breeding with focus on plant's physiology (Whan et al. 2010), which could be highly beneficial in breeding programs.

Mycorrhizal association Improves the plant's nutrient uptake particularly P. Reis et al. (1999) observed the presence of 14 distinct arbuscular mycorrhizae (AM) species among which *Glomus* was the most representative. Crop rotation also benefited the mycorrhizal association (Ambrosano et al. 2010) and improved cane yield by 30% in addition to improvement in sugar content. Though sugarcane's genetic potential for mycorrhization is still elusive, sugarcane geneticists and physiologists should put efforts in providing tools to enable breeding programs to create genotypes with higher mycorrhization potential, which would certainly have great impact on crop management costs, plant's fitness to adverse conditions and plantation sustainability.

Genetic variations were observed in the response of sugarcane genotypes to CO_2 enriched atmosphere. de Souza et al. (2008) analyzed Brazilian sugarcane varieties grown for 50 weeks under normal (360 ppm) and double CO_2 conditions (720 ppm). Double CO_2 increased photosynthesis by 30%, accumulated 40% more biomass and had higher water-use efficiency. Microarray analysis indicated that 35 genes were differentially expressed in leaves - 14 genes were repressed and 22 genes were induced. Vu and Allen (2009a) tested two varieties grown in double CO_2 conditions and observed that the responses were positive in terms of productivity and water use efficiency but the magnitude varied between the varieties.

Sugarcane varieties with improved constitution of cell wall contents to yield more cellulose and less lignin (Pandey et al. 2000; Ragauskas et al. 2006), varieties amenable for mechanical harvesting with low environmental impact, varieties for use of the whole aerial plant parts as substrate for ethanol production and genetically improved yeast strains with higher enzymatic capacity, including fermentation of pentoses, are some of the other molecular approaches suggested to mitigate climate change.

Increased rooting depth, increased intrinsic water use efficiency and, to a lesser extent, reduced conductance leading to increased transpiration efficiency are suggested as the best traits to consider for selection of sugarcane clones in water-limited environments in the tropics and sub-tropics (Inman-Bamber et al. 2012).

b. Soil carbon sequestration in sugarcane farming system

Sugarcane plantation could substantially sink more soil carbon than matured or secondary forests (Edicha 2010). Conservation farming practices, no-till farming and good fertilizer placement increase soil organic carbon levels helping to offset the GHG emissions. Reducing GHG emissions simply means that crops and livestock are raised more efficiently, thus reducing wasteful input losses like N (N_2O) and energy (CH_4). Technologies for both reducing the mineralization rate constant and enhancing the SOC will reduce the CO_2 emission into the atmosphere. Increase in soil organic matter pool by 1 t C/ha/yr was estimated to increase food production by 30–40 Mt in developing countries (Lal 2006).

Crop residue management

Addition of organic manures and sugarcane residues was found to improve the SOC concentration and C-sequestration potential of sugarcane. Removal of crop residue not only depletes soil organic matter and other recyclable nutrients but also declines soil structure and increase soil erosion (Wilhelm et al. 2004). Suman et al. (2009) found that a minimum addition of 3.9 t C/ha/yr in the form of recycled sugarcane biomass maintained the SOC without any deterioration. After five years of sugarcane residue recycling, the SOC increased by 17.1 t/ha over the initial content.

In India, though green harvest is practiced, the dry trash and unused tops are burnt after harvest contributing significantly to CO_2 emission. Green harvest and incorporation of trash into the soil not only reduce the CO_2 emission but also N_2O emission. De Figueiredo and Scala (2011) estimated that application of synthetic N fertilizer and burning of residues in sugarcane released 1167.6 and 941.0 kg CO_2eq.GHGs/ha/yr, respectively while burnt harvest released 3103.9 kg CO_2 eq./ha/yr and hence the scope for reducing GHGs from sugarcane field was from 310.7 to 1484.0 kg CO_2 eq./ha/yr.

Thorburn et al.(2012) estimated that mature sugarcane crop yields 13-20 t/ha of residue biomass which contains useful plant nutrients and C. The practice of retaining rather than burning sugarcane crop residues may increase total soil organic C by 2 g/kg after 6 years of incorporation (Robertson and Thorburn 2007 a & b), by 5 g/kg after 8 years of incorporation (Galdos et al. 2009) and by 9.2 g/kg after 55 years of incorporation (Canellas et al. 2010). Razafimbelo et al. (2006) have recorded that incorporation of trash and residues corresponding to 14% of above ground sugarcane biomass into soil added 0.65 t C/ha/yr at 0–10 cm depth. Cerri et al. (2004) have also indicated that trash, if not burnt, can add 0.53 t C/ha/yr. Cultivation of sugarcane for five years without residue incorporation depleted 7.3% of the initial SOC content. The incorporation of organic matter or chemical fertilizer reduced the decay rate constant. Addition of organic matter directly or through residue management increases SOC which ultimately helps in sequestering atmospheric CO_2 into SOC by increasing plant growth and subsequently returning more organic C to the soil.

The burning of sugarcane residues also releases other GHG or GHG precursors, including carbon monoxide (CO), methane (CH_4), non-methane volatile organic compounds (NMVOC) and N (N_2O, NOx) species (Levine 2000). The GHG emission due to sugarcane burning depends on the amount of residue available and sugarcane yield. The mean CO_2 emission was 39% higher in trash burning (2.87 mmol/m^2/s) when compared to the unburnt plot (2.06 mmol/m^2/s)during 70d period after harvest (Panosso et al. 2009).

Sequestration of the incorporated sugarcane residues is site dependent due to multiple influences on soil organic C like soil, climate, crop, management practices, soil fauna, etc. (Thorburn et al. 2012). Soil C decreased by 0.9 g/kg and 0.5 g/kg at sites where residues had been retained for one and 17 years, respectively, but increased by 2.0 g/kg at a site with residues retained for six years.

Tillage management

Less intensive tillage, reducing the use of bare fallow, choice of crops and their rotation aimed at returning crop residues to the soil, and integrated nutrient management, etc. aid in SOC sequestration (Dhillon and von Wuehlisch 2013). Biggs et al.(2012) through a simulation study found that the N loss from heavily tilled and high N fertilized plot was 31 kg N/ha/yr and from minimum tillage and optimum N fertilized plot, it was 3 kg N/ha/yr, i.e. a 90% decrease through management practices alone. As discussed earlier, each kg of N saved is equivalent to 0.86 kg of C in the form of fossil fuels. The soil carbon content in zero soil disturbance crop production and retaining all crop residues showed an increase of 1.0-1.6% in nine years (Starritt 2010).

Manure and nutrient management

Fertilized soil releases more than 2 billion tonnes of CO_2 equivalent GHGs every year. Nitrogen applied in manures and fertilizers is not always used efficiently by crops. Improving this efficiency can reduce emissions of N_2O generated by soil microbes largely from surplus N and it can indirectly reduce emissions of CO_2 from N fertilizer manufacture. Practices that improve N use efficiency include: adjusting application rates based on precise estimation of crop needs, using slow-release fertilizer forms or nitrification inhibitors, avoiding time delays between N application and plant N uptake, placing the N more precisely into the soil to make it more accessible to roots, avoiding excess N applications, or eliminating N applications where possible.

Organic farming

Organic farming is thought to contribute to GHG mitigation as it has a much reduced consumption of fossil fuels for energy, less vulnerability of soils to erosion, an increase in carbon sequestration due to the recycling of nutrients and other techniques aimed at building up soil fertility (Dhillon and von Wuehlisch 2013).

Biochar from sugarcane residues

Biochar is charcoal produced by pyrolysis of biomass under restricted oxygen environment at higher temperatures ranging from 400°C to 1500°C and primarily used for biofuel and carbon sequestration. It is also used to improve water quality, increase soil fertility, raise agricultural productivity and reduce pressure on old-growth forests. Biochar is a stable solid, rich in carbon content, and resistant to microbial degradation and thus, can be used to lock carbon in the soil. Converting the biomass into biochar breaks the regular carbon dioxide cycle and the cycle transfers favourably towards carbon sequestration.

The biochar from crop residues is produced by burning them at temperatures ranging from 400 to 500°C in a low oxygen environment in a pyrolyser. Sugarcane dry trash and bagasse were found to yield about 30 - 33% bio-char along with flu gas and liquid. The process is thought to have been discovered by accident (Starritt 2010). It was a practice carried out in ancient times where natural biomass plant material was covered with soil and left to smoulder with an intention to produce charcoal as an early fuel source. The pits used for the process contained dark soil which when placed around plants produced rapid growth and the product was discovered to be rich in nutrient. This was also spread across crops as a source of fertilizer. Further analysis has uncovered that the treated sites were able to hold greater amounts of water and nutrient and also enhance carbon storage in soil (Dhillon and von Wuehlisch 2013).

A commercial slow pyrolysis unit could generate over 1 MWhr of electricity from every two tonnes of trash (dry basis), with a biochar recovery of 31.3 - 33.6%. One tonne of bagasse derived biochar would sequester 2.3 tonnes of CO_2 equivalents. In addition to C sequestration, biochar has other significant benefits (when used as a soil amendment) such as improved soil quality, higher CEC and nutrient availability, and improved soil physical characteristics. Biochar application also reduces emissions of greenhouse gases from sugarcane soils, such as nitrous oxide (Quirk et al. 2012). Slow pyrolysis and biochar utilization in the sugarcane industry has the potential to provide (1) renewable energy (2) income from waste (3) climate mitigation through stabilization of carbon and (4) climate mitigation through reduced emission of N_2O from soil. Kuzyakov et al. (2009) estimated that biochar made at temperatures of 400°C may have a turnover rate of around 2000 years.

Phytoliths from sugarcane

Phytoliths are found in many plants particularly grasses and are prolific in sugarcane which is grown worldwide. Also referred to as 'plantstones' or 'plant opal', phytoliths are silicified cell structures that occlude carbon (Wilding et al. 1967). The silicified epidermal cells of the leaf and stem within all grasses are particularly good at occluding carbon (Parr and Sullivan 2005). This carbon fraction is likely made up of the internal cytoplasmic organic cellular material (Wilding et al. 1967). Upon harvest the leaf material is deposited onto the soil surface and the phytoliths later become incorporated into the soil matrix during decomposition of the plant organic material.

The carbon content of phytoliths of different sugarcane varieties ranged from 0.12 to 0.36 t e-CO_2 /ha/yr. Significant variations in the phytolith occluded carbon (PhytOC) content was observed among varieties which was independent of the quantity of silica in the plant revealing the variations in the efficiency of carbon encapsulation by individual varieties (Parr et al. 2009; Starritt 2010). This PhytOC process reduces emissions from agriculture in the long-term (millennia), as opposed to many other soil organic carbon fractions that may decompose over a much shorter time. The phytolith content of most A horizons of soils was <3% but in some soil horizons the phytolith content was as high as 30% (Parr and Sullivan 2005). The PhytOC yield of sugarcane was 18 g $C/m^2/yr$ which was 30 times higher than the mean PhytOC yield of natural vegetation and 7.5 times greater than the global mean soil carbon sequestration rate under natural vegetation. The soil carbon sequestration rate of a high PhytOC yielding sugarcane variety was ~0.4 t eCO_2/ha/yr greater than that of a low PhytOC yielding sugar cane variety. Growing high PhytOC yielding variety over ~20 M ha worldwide was estimated to result in the secure soil carbon sequestration of an additional 8 Mt eCO_2 every year from sugarcane alone.

c. Bio-fuel and climate change mitigation

Bio-fuels like ethanol and biodiesel are considered green fuels as these fuels recycle the atmospheric CO_2 and transform solar energy to fuel energy needed particularly for the transport sector and at the same time sequestering C in the soil through extensive root systems (Jansson et al. 2010). Sugarcane based ethanol may reduce the GHG emissions by 80% or more over the whole production and use cycle, relative to emissions from fossil fuels (Wreford et al. 2010).

All over the world, governments have initiated the use of alternative sources of energy for ensuring energy security, generating employment, and mitigating CO_2 emissions. India started its biofuel initiative in 2003. This initiative differs from that of other nations in its choice of raw material for biofuel production, i.e. molasses for bioethanol and nonedible oil for biodiesel. A coherent, consistent, and committed policy with long-term vision can sustain India's biofuel effort. This will provide energy security, economic growth, and prosperity and ensure a higher quality of life for India (Gopinathan and Sudhakaran 2009).

d. Role of sugar industry in tackling the climate variability

Sugarcane industry worldwide is exposed to uncertainty associated with variable climate. This variability produces impacts across an integrated value chain that comprises cane cultivation, harvest and transport, milling and marketing. Integration of seasonal climate forecasting with management strategies has the potential to benefit sugar industry in many areas (Muchow et al. 2001). Farm advisories based on climate variability will help improve on-farm profitability through better use of water resources, increased water use efficiency and higher sugar production, with minimal movement of nutrients and pesticides off the farm reducing the potential harmful environmental consequences of sugarcane production. Planned planting operations based on climate variability help to improve scheduling of milling operations leading to more effective use of resources like milling capacity, haulage equipment, shipping, etc. (Everingham et al. 2002).

Conclusion

There is general agreement on the emerging overall climate change scenario which will feature increased temperature in most parts of the country, drought situation due to reduction in soil moisture and increased water requirement for irrigation. The yields will be reduced and there could be reduction in sucrose content depending upon the region. There could be improvements in yield in colder regions of the country, where the elevated temperature and CO_2 levels will favour better growth. There will be changes in rainfall pattern with increase in some areas and deficit in some other regions. Consequently there will be problems on account of drought and waterlogging. There will be increased CO_2 availability which will favour enhanced growth in C3 plants resulting in increased weed growth affecting sugarcane productivity. Increased temperature will result in gross changes in disease and pest scenario. New pathotypes may emerge in the case of red rot. Minor diseases and pests may become major ones, warranting surveillance and constant monitoring. The increase in CO_2 levels or temperature alone may not be the deciding factors that are likely to impact sugarcane productivity. The varietal responses to various parameters of climate change may vary widely which also need to be considered. Strategies for sustaining the productivity under the climate change scenario include improving the adaptive response of varieties, management of the associated risks by providing weather linked value-added advisory services to farmers, crop insurance and improved land and water use management (Aggarwal, 2009). Breeding climate resilient sugarcane varieties, residue recycling, biochar production and application, PhytOC efficient varieties, sugarcane based bio-fuels are some of the sound options for mitigating climate change in sugarcane farming.

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