Sugarcane: Contribution of Process-Based Models for Understanding and Mitigating Impacts of Climate Variability and Change on Production

8

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Abstract

Sugarcane is cultivated on about 26 M ha across tropics and subtropics worldwide as a source of many industrial products, especially sugar and also bioenergy purposes (biofuel as ethanol and electricity). As the crop is grown in a wide range of climates, soils, and countries, different cropping systems are adopted across producing areas, resulting in large genotype × environment × management interactions, consequently large variations in yield levels are found. Climate and its variability and change play an important role in plant processes. In this chapter, a climate characterization of the main producing countries is presented along with the influence of main weather variables on sugarcane growth, development, and yields. The key variables of climate change are also explored. The effect of weather conditions on key sugarcane yield-building processes are well captured by process-based models. Two are embedded in the well-known and readily available agricultural systems modeling platforms; DSSAT/CANEGRO and APSIM-Sugar. These two models and a third (WaterSense) are described briefly with highlights of recent improvements and weaknesses. Finally, this chapter lists a series of application papers found so far in literature that included, at least to some extent, the intrinsic effect of climate and its variability mostly based on long-term weather data series. Special focus is then given to irrigation and nitrogen management, yield analysis (gaps, benchmarking, and forecasting), climate change issues, drought adaptation, and breeding studies. Even though

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M. Ahmed (ed.), *Systems Modeling*, https://doi.org/10.1007/978-981-15-4728-7_8

sugarcane models have some weaknesses, they are considered as powerful tools for understanding and proposing management and adaptive actions to mitigate or increase yields in risky climates, in the present or future.

Keywords

Saccharum spp. · Crop modeling · Sustainability · Review

8.1 Introduction

Sugarcane (*Saccharum* spp.) is grown in the tropics and subtropics around the world as a source of food (mainly as sugar, and also as molasses), bioenergy (biofuel as ethanol and electricity), and others (for instance, alcoholic beverages and chemicals). Sugarcane products (especially sugar) are important components of the economy of many countries worldwide, many of which are developing countries. Sugarcane is produced by nearly 100 countries and occupies roughly 26 M ha of land (Table 8.1;

Table 8.1 Sugarcane production, area, and yield of the 20 largest producing countries worldwide in 2017 (FAO 2019)

Country	Production (M t)[a]	% Total	Area (M ha)[b]	% Total	Yield (t/ha)
Brazil (BRA)	758.5	41.19	10.18	39.2	74.5
India (IND)	306.1	16.62	4.39	16.9	69.7
China (CHN)	104.8	5.69	1.38	5.3	76.1
Thailand (THA)	102.9	5.59	1.37	5.3	75.2
Pakistan (PAK)	73.4	3.99	1.22	4.7	60.3
Mexico (MEX)	57.0	3.09	0.77	3.0	73.8
Australia (AUS)	36.6	1.99	0.45	1.7	80.6
Colombia (COL)	34.6	1.88	0.40	1.5	87.2
Guatemala (GTM)	33.8	1.83	0.28	1.1	121.0
United States (USA)	30.2	1.64	0.37	1.4	82.4
Philippines (PHL)	29.3	1.59	0.44	1.7	66.9
Indonesia (IDN)	21.2	1.15	0.43	1.7	49.3
Argentina (ARG)	19.2	1.04	0.38	1.5	50.6
Viet Nam (VNM)	18.4	1.00	0.28	1.1	65.3
South Africa (ZAF)	17.4	0.94	0.26	1.0	65.7
Cuba (CUB)	16.1	0.87	0.39	1.5	41.5
Egypt (EGY)	15.3	0.83	0.14	0.5	112.7
Myanmar (MMR)	10.4	0.56	0.16	0.6	63.5
Peru (PER)	9.4	0.51	0.08	0.3	121.2
Ecuador (ECU)	9.0	0.49	0.11	0.4	81.6
Others	138.2	7.50	2.51	9.7	55.1
Overall	1841.5	100.00	25.98	100.00	70.9

[a]M t, mega tonnes (metric tons $\times 10^6$)
[b]M ha, mega hectare (ha $\times 10^6$)

FAO 2019). The largest producer is Brazil, followed by India, China, and Thailand, which together produce more than two-thirds (~ 69%) of the entire world's sugarcane (Table 8.1).

A spatial view of sugarcane production by each country can be found in Fig. 8.1. The crop is grown between roughly 35° north and south of the equator, where a wide range of climates is found. A comparison between producing regions in terms of climate in some countries is presented in Sect. 8.2. In addition to the variability faced year by year, climate is changing arguably due to anthropic greenhouse gases emissions, and further changes are predicted by climate scientists of the Intergovernmental Panel on Climate Change (IPCC 2014). Increments in global temperatures and weather extremes such as heat and cold waves, drought, and flooding are likely to be more severe and more often, which will affect agriculture, livestock, location and production from forestry, and many others sectors of society and environment (IPCC 2014). Hence, it is important to develop an overall understanding of sugarcane production systems worldwide to assess its vulnerability to climate change and adaptation strategies. The sugarcane industry has a considerable potential to offset greenhouse gases emissions (Börjesson 2009) considering its capability to produce renewable energy (bioelectricity and ethanol). Thus it is likely that the cultivated area with this crop will increase in regions where land is available for expansion, like under degraded pastures in Brazil (Goldemberg et al. 2014; Alkimim and Clarke 2018).

A wide variety of production systems have evolved across the world in response to local climates and soils as well as the availability of resources and genetic material. Traditional and evolving arrangements between growers and millers and scales of production also influence the way the crop is grown and delivered for processing. The range of genotypes (varieties), planting dates and crop ages, row spacings, irrigation methods, harvest methods, residue management, crop nutrition (especially nitrogen), and pest, weed and disease control methods is large. Thus, there are large genotype × environment × management (G × E × M) interactions that affect crop growth, development, yield, and quality. Differences in yield levels between producing countries can be found in Table 8.1. A basic understanding of

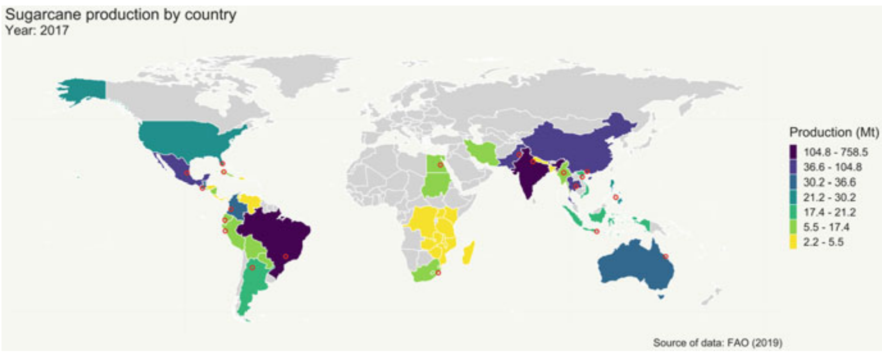

Fig. 8.1 Schematic representation of production quantities of sugarcane by country in 2017. Red circles represent the 20 largest producing countries

sugarcane yield-building processes responsive to climatic factors, including elevated CO_2 and high temperature, is described in Sect. 8.3.

Mechanistic or process-based crop models are useful tools that integrate crop/genotype, weather/climate, and soil and management practices and can be used to help with the understanding of G × E × M interactions, thus serving as powerful tools for several sectors, such as consulting, farmers, agro-industry, government, and policy makers (Boote et al. 1996; Lisson et al. 2005; Singels 2014; Wallach 2006). In Sect. 8.4 we briefly describe crop models dedicated to sugarcane and summarize the history of the two most important ones, with details of their most recent improvements. Applications of sugarcane models for sustainability of the cropping systems regarding irrigation, nitrogen fertilization, yield gap analysis, yield forecasting, impacts of climate change, drought adaptation and breeding are also shown and discussed in Sect. 8.5.

This chapter therefore aims to present the main sugarcane models and their role in understanding and mitigating the impacts of climate variability and change on sugarcane systems toward sustainable crop production.

8.2 Climate of Sugarcane Growing Regions Around the World

Climate is the average condition of weather variables at a given spatial scale (for instance farm, site, region, or country) in a given time scale (for example, month and year), thus, has a static pattern. The climate is influenced by basically two types of factors: fixed and changeable. Latitude, altitude, distance of water bodies and main oceans, and air and snow currents can be categorized as fixed factors. On the other hand, changeable factors drive the variability within the same area and are influenced by global, regional and local circulation of atmosphere. An important phenomenon that affects climate variability worldwide, and thus crop yields, is the El Niño–Southern Oscillation (ENSO), and also others like the Indian Ocean Dipole (IOD), the North Atlantic Oscillation (NAO) and Tropical Atlantic Variability (TAV) (Heino et al. 2018; Anderson et al. 2019).

Regarding climate variables for sugarcane growing regions, the monthly maximum air temperatures across sites range from 19 °C (January at Nanning, CHN) to 45 °C (June at Faisalabad, PAK), whereas minimum temperatures range from 6 °C (July at Tucumán, ARG) to 31 °C (July at Faisalabad, PAK). Annual solar radiation ranges from around 5000 MJ/m^2/year (at Nanning, CHN) to more than 7000 MJ/m^2/year (at sites in EGY, PER, AUS, IDN, and GTM). Radiation and temperature are the main drivers of sugarcane biomass accumulation under non-limiting (potential) conditions (Muchow et al. 1997b; Inman-Bamber 2014; Sage et al. 2014). Rainfall, evaporation from the soil and plant transpiration (evapotranspiration), air humidity, and wind speed also affect yields and demand for irrigation (Thornthwaite 1948; Allen et al. 1998; Inman-Bamber and McGlinchey 2003).

Rainfall varies through the year in all sugarcane countries and some monsoonal countries have extremes with excessive rain in some months and very little in others (Fig. 8.2). Sugarcane is grown in desert areas, such as in EGY, PER, and MMR,

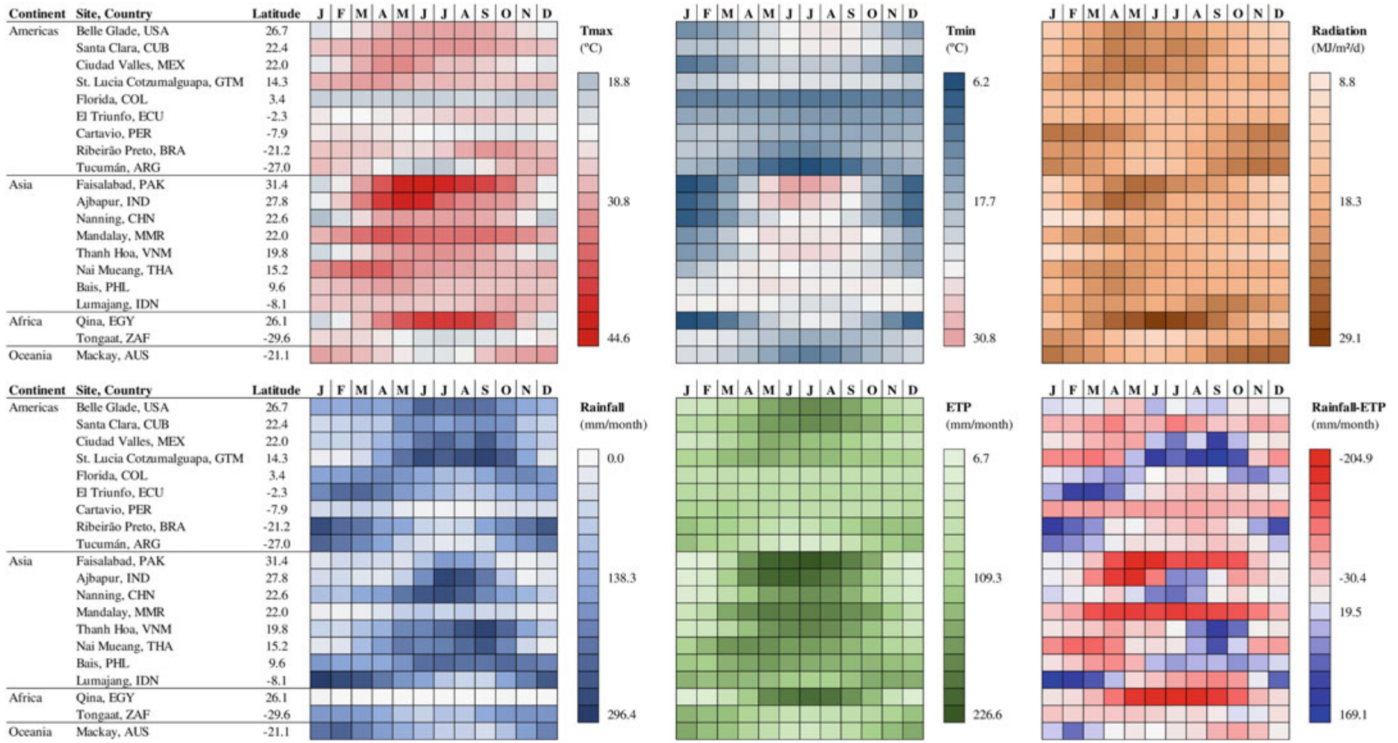

Fig. 8.2 Comparison of main monthly average climate variables driving sugarcane yield at important sites in the 20 largest producing countries highlighted in Fig. 8.1
Source of data: NASA/POWER Agroclimatology database (https://power.larc.nasa.gov/data-access-viewer/)
Where Tmax and Tmin are maximum and minimum air temperatures, respectively, and ET is the potential evapotranspiration estimated by Thornthwaite (1948)'s method

where average annual rainfall is less than 200 mm, and also in regions where rain is more than 1500 mm, such as in GTM, PHL, and IND. Annual potential evapotranspiration ranges from 719 mm (at Florida, COL, highest place in terms of altitude) to more than 1600 mm (at Mandalay, MMR). An integrative index called annual water deficit, represented by the difference between rainfall and potential evapotranspiration, can also be employed to compare the climate across sugarcane growing regions. This index varies between −36 mm (at Florida, COL) to less than −1311 mm at sites in MMR, EGY, and PAK. On the other hand, there are areas with excess of water, especially in the monsoon months, such as those in the tropics where annual rainfall surpasses potential evapotranspiration by more than 500 mm (GTM and IND).

Even in the same country, many types of climate and degrees of variability are found, therefore, the better the understanding of the climate where the crop is grown, the lower the risk of failure for new decisions and business plans. Climate zones (CZ) may be distinguished within a production region based on homogeneity in weather variables that have the greatest influence on crop growth and yield (van Wart et al. 2013). CZs already exist for the South African sugar industry (Bezuidenhout and Singels 2007a) and are used as a basis for providing forecasts of sugarcane yield using a model-based system (presented in Sect. 8.5.4).

A recent spatial analysis framework called “technology extrapolation domain” or TED (Edreira et al. 2018) couples soil with climatic factors and aims to facilitate the assessment of cropping system performance across producing regions, including continents, which in turn could facilitate the sharing of better management practices toward improved yields. A simulation study with wheat in Argentina and Australia was done to show the potential of the TED approach. The study revealed that an annual rainfed double-crop (as adopted in Argentina) of wheat-mungbean would be a superior alternative to the crop-fallow system that currently predominates in the analog TED in Australia. While the use of CZs or TED approaches in the sugarcane industry could be highly beneficial, the only country to adopt this approach to date is South Africa. These types of approaches would also be useful for understanding and adapting the current sugarcane production systems worldwide to changing climates.

8.3 Climate Influence on Sugarcane Performance

The performance of a particular crop, ultimately yields, can be categorized in terms of the following levels (Rabbinge 1993; van Ittersum and Rabbinge 1997; Evans and Fischer 1999; Lobell et al. 2009; van Ittersum et al. 2013; Fischer 2015):

- Potential yield (Yp): yield of a given cultivar grown in an environment to which it is adapted that is not significantly affected by water, nutrients, lodging, and biotic factors; being determined by solar radiation, air temperature, photoperiod, CO_2 concentration, and other air constituents (determining factors).

- Water-limited yield (Yw): similar to Yp, but influenced by water stress (limiting factor) as determined by rainfall amount and distribution along the crop cycle, evapotranspiration, soil water holding capacity, and topography.
- Water- and nutrient-limited yield: Yw plus nutrient deficiency (ies) and other limiting factors.
- Attainable, exploitable, or economic yield: yield attained by farmers or a particular agro-industry with average natural resources when economically optimal practices and levels of inputs have been adopted while facing all the vagaries of weather in rainfed, supplementary- and full-irrigated cropping systems.
- Actual or average yield (Ya): yield actually obtained by farmers or a particular agro-industry, considering the determining, limiting, and also reducing factors associated with pests, diseases, weeds, and mechanical (harvester) damage.

Apart from its role in determining, limiting, and reducing factors that affect sugarcane yield, climate also indirectly limits industry performance by affecting field operations, and the transport, processing, and marketing of sugar (Muchow et al. 1997b), and other products such as ethanol. While climate is important for these processes, only yield determining and limiting processes are considered in this chapter.

Before moving into climate interactions with the crop, a brief elucidation of sugarcane plant is needed. Sugarcane species (*Saccharum* spp.) are generally large, perennial, tropical, or subtropical grasses that evolved in environments with high radiation incidence, high air temperatures, and large quantities of water (Moore et al. 2014). Commercial sugarcane genotypes are complex interspecific hybrids primarily between *Saccharum officinarum* L. (also known as noble canes) and other species (Moore et al. 2014). According to (Bonnett 2014), sugarcane phenology can be divided into the following stages: (1) germination from true seed or sprouting of buds (from culm pieces or ratoons), (2) leaf development, (3) tillering, (4) stalk elongation, (5) development of harvestable stalks, (6) maturation (sucrose accumulation), and (7) flowering.

For commercial purposes, mainly for sugar production, the ideal climate for sugarcane according to (Mangelsdorf 1950) is "a long, warm growing season and a fairly dry, cool, but frost-free, ripening and harvest season, free from hurricanes and typhoons". As previously shown, however, sugarcane is grown in a wide range of environments and many of these would never experience such ideal conditions over a given crop. Furthermore, inter- and intra-seasonal meteorological conditions during crop growth and development influence the yield-building and yield-limiting processes of sugarcane, culminating in different levels of yields (Muchow et al. 1997b; Inman-Bamber 2014).

As sugarcane is planted with culm pieces in most industries worldwide, the following description is based on this type of planting strategy. After planting or harvesting, sprouting strongly depends on temperature and on soil water to some extent (Yang and Chen 1980; Donaldson 2009; Smit 2010). Compared to other C_4 plants, such as maize, sorghum, and napier grass, sugarcane grows slowly during the early part of its growth period, characterized by rates of leaf and tiller production

(Allison et al. 2007). Leaf and tiller production are both dependent on temperature, soil water (Inman-Bamber 2004), and management (Bell and Garside 2005; Singels and Smit 2009), all of which affect light interception by the canopy. The characteristic initial slow growth of sugarcane is responsible for "wasting" radiation in the first few months (Inman-Bamber 2014). Generally, the warmer the climate, the faster is the canopy development and the greater is the proportion of incident radiation captured by the crop (Inman-Bamber 1994; Donaldson 2009; Dias et al. 2019).

As the sugarcane canopy develops, the ratio of leaf to ground area (leaf area index or LAI) increases as does solar radiation interception and biomass production. Solar radiation (approximately 300–3000 nm) is an important component of the energy and water balances affecting crop growth and development, but photosynthetically active radiation (PAR, 400–700 nm) is the component of radiation that is important for the carbon balance and, hence, biomass accumulation. Canopy closure occurs when 70% of PAR is intercepted by leaves, which depends on climate and variety, as well crop management (Inman-Bamber 1994, 2014; Singels and Smit 2009). Leaf and stalk initiation, elongation, and senescence are to a large extent influenced by temperature and water stress (Inman-Bamber and Jager 1988; Inman-Bamber 1995, 2004; Robertson et al. 1996, 1998; Sinclair et al. 2004; Inman-Bamber and Smith 2005; Grof et al. 2010). However, Robertson et al. (1999a, b) found that water deficits imposed during the tillering phase (LAI < 2), while having large impacts on leaf area, tillering, and biomass accumulation, had little impact on final yield. Many other factors in the $G \times E \times M$ interaction during the long growth cycle of sugarcane influence its biomass yield at harvest.

Biomass accumulation can be expressed in terms of radiation use efficiency (RUE). RUE can be defined as the mass of aboveground biomass accumulated by a crop per MJ of solar radiation or of PAR intercepted or absorbed by the green leaf canopy (Monteith 1972; Sinclair and Muchow 1999; Bonhomme 2000). Sugarcane is one of the most efficient crops in terms of RUE (Sinclair and Muchow 1999), associated with high C_4 rates of photosynthesis (Sage et al. 2014), a long growing season (Inman-Bamber 2014), and low metabolic cost of plant organs (de Vries et al. 1989). RUE ranging between 1.38 g MJ^{-1} and 2.09 g MJ^{-1} are found in literature (Robertson et al. 1996; Muchow et al. 1997a; da Silva 2009; Singels and Smit 2009; De Silva and De Costa 2012; Ferreira Junior et al. 2015), which appears to be strongly controlled by temperature during sugarcane growth (Donaldson 2009). However, a recent study suggest that this trait is quite conservative between elite varieties across production countries (Dias et al. 2019).

An important constraint in sugarcane yield, mainly in high input conditions, is known as reduced growth phenomenon or RGP (Park et al. 2005; van Heerden et al. 2010). RGP was recognized in an indirect way in the past by authors such as Rostron (1974), Lonsdale and Gosnell (1976), Thompson (1978), Inman-Bamber and Thompson (1989), and Muchow et al. (1994). Factors such as lodging, reduced nitrogen leaf content, stalk loss, negative feedback of sucrose accumulation on photosynthesis, and increasing maintenance respiration during development and maturation (sucrose) have been associated with RGP, but none of these causes have been clearly defined. Those factors for which meteorological conditions play an important role are discussed next.

Lodging disrupts the canopy, damages stalks, and reduces yield through reducing RUE in high-yielding areas where roots may be poorly supported in wet soil and a wet canopy raises the crop's center of gravity and in windy conditions (> 200 km d^{-1}) (Singh et al. 2002; van Heerden et al. 2010). Field experiments in Australia (Singh et al. 2002) and South Africa (van Heerden et al. 2010) showed that lodging reduces cane yields by 7.3–15% and sucrose yields by 8.8–35%, depending on the variety and weather conditions.

The larger the biomass, the higher the maintenance respiration, which is also increased with temperature up to a certain point (de Vries et al. 1989; Liu and Bull 2001; Jones and Singels 2019). It is likely therefore that global warming will exacerbate the maintenance respiration rates of sugarcane. In high-yielding areas where temperatures are consistently high, this process could be important for biomass accumulation during the late stages of the growth cycle, thus contributing to RGP (van Heerden et al. 2010). Maintenance respiration also depends of the type of tissue (de Vries et al. 1989; Jones and Singels 2019) being maintained. A finding in the van Heerden et al. (2010) study, based on data from well-watered and well-managed crops in South Africa (Donaldson et al. 2008), was that crops which started in summer (December) gave lower yields than those starting in winter (July). In summer crops, the slowdown commenced in the next spring due to low temperatures, but then persisted after temperatures rose again. Maintenance respiration of high biomass yields in summer was thought to be a limiting factor for sugarcane yield of summer crops.

Flowering, an undesired stage for commercial purposes (Moore and Berding 2014), is highly dependent on climate. After an initial juvenile stage of 2–3 months, a decline of photoperiod (or day-length) from 12.5 to 12.0 h per day can lead to flower induction in an unstressed crop and, in most cases, the emergence of the inflorescence (Bonnett 2014; Moore and Berding 2014). As the photoperiod is entirely latitude-dependent, the window for flower induction is easily found through astronomical equations. Temperature also plays an important role in sugarcane flowering which is favored by values higher than 18.3 °C (Coleman 1963) and lower than 32 °C (Berding and Moore 2001), but other factors such as water and nutrient status, genotype, and crop age also have their influence (Gosnell 1973; Moore and Berding 2014). Thus, flower induction and emergence are highly dependent on climate and its variability.

8.3.1 Climate Change-Related Environmental Variables

The global concentration of atmospheric CO_2 is currently around 411 ppm (NOOA 2019), about 147% higher than pre-Industrial Revolution levels in the nineteenth century (~ 280 ppm). Elevation of CO_2 and other greenhouse gases with current and future emission scenarios will lead to changes in climate patterns worldwide (IPCC 2014). Therefore, it is crucial to understand how sugarcane plants and cropping systems will be influenced by changing climates in order to predict impacts and to design adaptive and mitigation actions.

The effect of CO_2 on agricultural crops has been extensively studied, but for sugarcane there are only a few studies that assess the impact of this gas on crop performance. Photosynthesis and biomass yields increased and transpiration decreased when CO_2 was increased to 720 ppm for 70–350 days in pot studies under near-optimum conditions (Vu et al. 2006; de Souza et al. 2008; Vu and Allen 2009a, b). The reported increments in photosynthesis might be influenced by reduced transpiration and better water relations and also by short-term measurements using small segments of leaves, not representing the whole-canopy (Stokes et al. 2016). Stokes et al. (2016) found no difference in photosynthesis or biomass yield at elevated CO_2 when plants were watered on demand, suggesting that the reported increments in biomass were due to water-related processes. Even under water stress, elevated CO_2 does not directly enhance C_4 species photosynthesis (Ghannoum et al. 2003). Sorghum and maize (C_4 crops) grown in free-air CO_2 enrichment field experiments (FACE) showed higher shoot biomass and yields only when water stress was imposed (Kimball 2016). It is known that crop responses to CO_2 in FACE experiments are lower than open-top chambers or glasshouses (Ainsworth et al. 2008). Although FACE experiments with sugarcane have not been reported so far, Stokes et al. (2016) presented model simulations to show how open canopy (FACE) conditions would dampen the response to CO_2 measured on single leaves or plants. Summing up, the CO_2 responses in sugarcane might be predominantly restricted to reductions in water use rather than an augmented photosynthesis rate, which is quite well represented with model simulations (Stokes et al. 2016; Jones and Singels 2019). It does not necessarily minimize the need for new experiments, particularly under field conditions, which will confirm or bring new evidence to this important matter.

Climate change is likely to increase the frequency and intensity of weather extreme events, such as droughts, floods, and heat and cold waves (IPCC 2014). Drought is a common concern and some countries have already started programs to improve varietal resistance to drought (Basnayake et al. 2012). Heat stress physiology is a topic that has received little attention in sugarcane research (Inman-Bamber et al. 2011; Lakshmanan and Robinson 2014). According to Lakshmanan and Robinson (2014), heat stress is an abiotic stress that refers to a condition in which plants experience irreversible physical or metabolic injury following exposure to a threshold temperature for a period of time that varies from species to species. Despite being adapted to warm climates, air temperatures beyond 40 °C affect sugarcane germination and shoot emergence, leaf phenology, and increase plant respiration (Bonnett et al. 2006; Lakshmanan and Robinson 2014; Jones and Singels 2019), thus affecting yields.

8.4 Process-Based Models Dedicated to Sugarcane

According to Wallach (2006) "crop models are mathematical models which describe the growth and development of a crop interacting with soil" that "consist of a set of dynamic equations that are integrated to get predictions of responses *versus* inputs". The dynamic nature of crop models is essential for simulating G × E × M interactions when climate variability and change are involved. Thereby, crop models can be used for many application studies (Boote et al. 1996; Wallach 2006), including some for the sugarcane industry (Lisson et al. 2005; Singels 2014).

This section presents the current crop models dedicated to sugarcane and summarizes the history and recent improvements for three of them after Singels (2014), highlighting their strengths and weaknesses. Simple statistical or empirical models (i.e. Thompson 1976; Kingston 2002; Cardozo et al. 2015) and those based on data mining techniques (i.e. Everingham et al. 2016; de Oliveira et al. 2017; Peloia et al. 2019) are not addressed here despite their usefulness in the conditions where they were developed and tested (see Chap. 4).

Process-based crop models found in literature that are dedicated to, or adapted for, sugarcane are listed in Table 8.2. Further details about some of them can be

Table 8.2 List of process-based sugarcane models

Model	Main references
Developed specifically for sugarcane crop	
CANEGRO	Inman-Bamber (1991), Singels and Bezuidenhout (2002), Singels et al. (2008), Jones and Singels (2019)
CANESIM	Bezuidenhout and Singels (2007a, b)
AUSCANE	Jones et al. (1989)
APSIM-Sugar	Keating et al. (1999), Thorburn et al. (2005), Inman-Bamber et al. (2016)
QCANE	Liu and Kingston (1994), Liu and Bull (2001)
WaterSense	Inman-Bamber et al. (2005, 2007), Armour et al. (2013), Stokes et al. (2016)
Singels & Inman-Bamber	Singels and Inman-Bamber (2011)
MOSICAS	Martiné (2003)
CASUPRO	Villegas et al. (2005)
SimCana	Machado (1981)
SAMUCA	Marin and Jones (2014)
Included in, or adapted from, other crop model platforms	
AquaCrop	Steduto et al. (2009), Bello (2013)
CropSyst	Stöckle et al. (2003), Tatsch et al. (2009), Scarpare et al. (2018)
SWAP-WOFOST	Qureshi et al. (2002), van Dam et al. (2008), Scarpare (2011), Boogaard et al. (2014)
ALMANAC	Kiniry et al. (1992), Meki et al. (2015), Baez-Gonzalez et al. (2018)
BioCro	Miguez et al. (2009), Jaiswal et al. (2017)
PS123	Driessen and Konijn (1992), van den Berg et al. (2000)
Agro-IBIS	Kucharik and Brye (2003), Cuadra et al. (2012)
STICS	Brisson et al. (1998), Valade et al. (2014)

found in Singels (2014) and the papers listed in Table 8.2. The majority of these sugarcane models are not available publicly and this limits model evaluation, intercomparison, identification of shortcomings for improvements and application.

Sugarcane models usually employ the concepts of yield levels as in Sect. 8.3 and are able to predict Yp and Yw at least, and some of them simulate the interaction with nitrogen and residues (such as APSIM-Sugar and QCANE). The time step of calculations is usually 1 day, but some sub-models operate hourly. Phenology or developmental stages are commonly driven by thermal time (or growing degree-days), using one or more cardinal temperatures. Light interception by the canopy is mostly simulated using Beer's Law (Monsi and Saeki et al. 1953, cited by Saeki 1963), where the exponent is the product of LAI and a light extinction coefficient. The amount of solar radiation or PAR intercepted is then converted via RUE to generate crop biomass. Some sophisticated photosynthesis and respiration sub-models are employed such as in BioCro, or a more simplified RUE-transpiration use efficiency (TUE) approach such as in APSIM-Sugar. The biomass produced, limited or not by environmental stresses, is then partitioned to several plant components or just to stalks or sucrose, via allometric fractions or a simple harvest index. A common limitation in many of the sugarcane models, including those with continuous improvements, is the lack of traits or parameters for varieties that are currently grown commercially. Efforts to improve a model's ability and applicability to simulate variety differences are rare in sugarcane modeling with a few exceptions (Cheeroo-Nayamuth et al. 2000; Singels and Bezuidenhout 2002; Suguitani 2006; Singels et al. 2010a; Singels and Inman-Bamber 2011; Sexton et al. 2014; Thorburn et al. 2014; Leal 2016; Hoffman et al. 2018; Dias et al. 2020).

The two models widely used and currently available, APSIM-Sugar and CANEGRO, are explored in Sects. 8.4.1 and 8.4.2, with a focus on recent improvements after the comprehensive review by Singels (2014). WaterSense is another important sugarcane model that was not explored in Singels' review, thus we review this model concerning its concepts and performance in Sect. 8.4.3. Lastly, strengths and weaknesses of the models are briefly explored in Sect. 8.4.4 and gaps for advancing the knowledge on sugarcane modeling are highlighted as well.

8.4.1 CANEGRO

The development of the CANEGRO model started in the 1980s after questions posed by South African sugar industry to their local sugarcane scientists. One of the key questions was in regard to the optimum crop age at harvest because of a problem with an important sugarcane pest (Eldana borer) particularly for crops older than 12 months (Inman-Bamber and Thompson 1989). South African Sugarcane Research Institute (SASRI, former SASEX) is the institution involved with past and present CANEGRO activities. CANEGRO modeling group is also involved with other initiatives such as the International Consortium for Sugarcane Modelling

(ICSM, https://sasri.sasa.org.za/agronomy/icsm/index.php) and The Agricultural Model Intercomparison and Improvement Project (AgMIP, http://www.agmip.org/).

A timeline of main events of CANEGRO development, reviews, and improvements is presented in Fig. 8.3, in which many of these events were described and detailed by Inman-Bamber (2000), O'Leary (2000), Lisson et al. (2005), Singels et al. (2008) and Singels (2014). Currently, the model is readily available in the Decision Support System for Agrotechnology Transfer (DSSAT, latest version 4.7.5, Hoogenboom et al. 2019) software.

Jones and Singels (2019) recently proposed improvements to CANEGRO regarding deficiencies found in the model, and in key plant processes influenced by changing climate variables (temperature and CO_2). Thermal time calculations, a main driver of canopy development and growth in the model, is now limited by high as well as low temperature. A simpler, more dynamic tiller sub-model that accounts for water and temperature stresses, bud population, and the shading effect of the developing canopy was implemented. Maintenance respiration for total biomass was replaced by respiration required for living tissue and the cycling of stored sucrose in the stalk. The CERES water stress approach (Jones and Kiniry 1986) was replaced with the simpler AquaCrop model (Steduto et al. 2009), which according to the authors, enables a more gradual and realistic transition from well-watered to water-stressed states. CO_2 effects are simulated by modifying the stomatal resistance term in the calculation of canopy resistance (Allen et al. 1985), which together with canopy radiation interception and sugarcane reference evaporation is used to calculate potential transpiration, following Singels et al. (2008) and Boote et al. (2010). The direct effect of CO_2 on sugarcane photosynthesis is accommodated in a new algorithm but will have no influence on photosynthesis with current or higher CO_2 levels unless new evidence from physiological studies shows otherwise (topic discussed in Sect. 8.3).

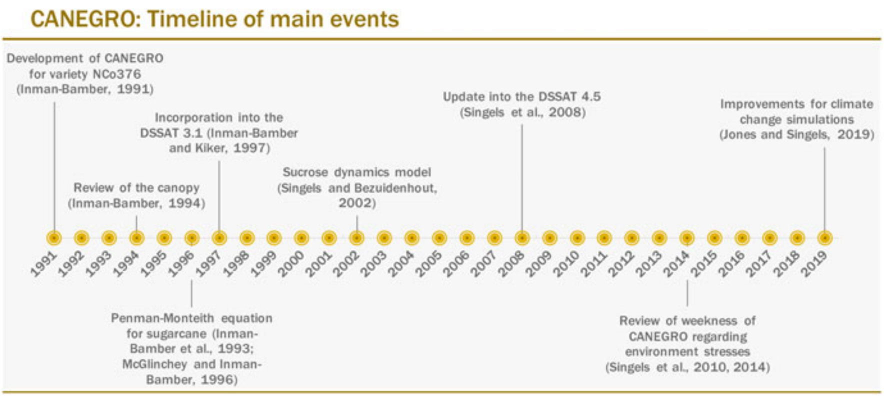

Fig. 8.3 Timeline of main events of the CANEGRO model currently embodied in the DSSAT cropping system

Although CANEGRO was built to benefit the South African sugar industry rather than other growing regions worldwide (Inman-Bamber 2000), many versions of the model have been successfully adapted for other varieties/cropping systems worldwide, including Brazil (Marin et al. 2011, 2015; Dias and Sentelhas 2017), Mauritius (Cheeroo-Nayamuth et al. 2003), and India (Bhengra et al. 2016). Recent improvements by Jones and Singels (2019) could well replace the various versions around the world given that the modifications have been introduced to make the model more representative of a wide range of varieties and cropping systems. This would help to concentrate testing and improvement on just one version for the model.

8.4.2 APSIM-Sugar

The Agricultural Production Systems SIMulator (APSIM) is a modular modeling framework that allows for farming system simulations according to a "plugged in/out" approach of desired modules, such as crop, soil and management practices (McCown et al. 1996; Keating et al. 2003; Holzworth et al. 2014). APSIM was first designed and developed in the early 1990s by a group called the Agricultural Production Systems Research Unit (APSRU) formed by a collaboration between regional Australian government agencies (Queensland State) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO). A module for sugarcane was built by Keating et al. (1999) as one of APSIM's many crop modules to overcome the weakness of key biological aspects of a previous widely distributed cane model in Australia called AUSCANE (O'Leary 2000). Currently, APSIM is an initiative headed by Australian and New Zealand organizations, in which the CSIRO is an important leader. Version control is a key aspect of their approach, so there is only one version of the "Sugar" module available for any one release of the APSIM platform.

A timeline of main events of APSIM-Sugar development, reviews, and improvements is presented in Fig. 8.4. Unlike CANEGRO, APSIM-Sugar's first version was evaluated across a diverse range of varieties and environments from Australia, South Africa, Swaziland, and USA (Hawaii) with considerable success (Keating et al. 1999; O'Leary 2000). The nitrogen and carbon cycles were important to the Australia sugar industry due to off-site impacts on the Great Barrier Reef and the impact of residues on water conservation, soil health, and mechanization. The nitrogen and residue modules were reviewed and improved in the early 2000s (Thorburn et al. 2005). Greenhouse gases emissions in sugarcane fields were also a target for model improvement in 2000s (Thorburn et al. 2010).

The sugarcane crop module itself has received little attention in terms of improvements since its development. The user is allowed a large degree of control through various parameter files and the model has been quite successfully adapted for other varieties/cropping systems worldwide, including Brazil (Marin et al. 2015; de Oliveira et al. 2016; Costa 2017; Dias and Sentelhas 2017), Mauritius (Cheeroo-Nayamuth et al. 2000) and USA for bioenergy grasses species (Ojeda et al. 2017). A

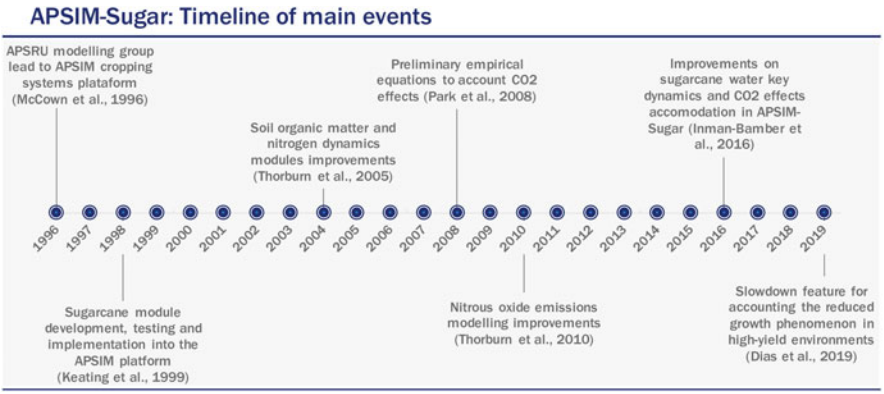

Fig. 8.4 Timeline of main events of the APSIM-Sugar model

preliminary assessment raised the question of whether APSIM-Sugar was able to predict yield differences between varieties after the inclusion of their specific phenology traits (Thorburn et al. 2014). The study suggested that vital phenology data for varieties may be deficient or the APSIM-Sugar model (and real sugarcane crops) are not overly sensitive to these traits when it comes to yield comparisons. Some of the model's shortcomings were recently raised and reasonably addressed by Inman-Bamber et al. (2012, 2016) and Dias et al. (2019), and are briefly described next.

Inman-Bamber et al. (2012) performed a theoretical study assessing traits for water-limited environments and found that transpiration efficiency and rooting depth were the ones with potentially important commercial impacts. Nevertheless, APSIM-Sugar lacked the capability for determining the trade-offs and interactions between traits. The shortcomings were later addressed by Inman-Bamber et al. (2016) resulting in the enhanced capability of APSIM-Sugar to simulate water-related physiological processes aiming to support crop improvement in breeding programs and to better distinguish between varieties in the model. The following four features were included and tested against the original dataset used for the model's development as well additional data from other field experiments: (1) the response of transpiration efficiency to water stress, (2) the midday flattening of hourly transpiration when plants are stressed, (3) conductance limits to hourly transpiration, which can apply even without stress, and (4) the separation of soil hydraulic conductivity (*k*) and root length density (*l*) rather than the use of a combined *kl* for determining root water supply. The new features allowed APSIM-Sugar to account well for observed yields and thus to accommodate genetic differences in stomatal conductance, responses to vapor pressure deficit, and differences in shoot:root ratio. The response of transpiration efficiency to CO_2 was also incorporated, in line with the CO_2 responses found in the literature for C_4 crops. No field data is yet available to validate the CO_2 response, however.

Dias et al. (2019) tested APSIM-Sugar in a new, hot environment where sugarcane is expected to expand in Brazil. Outstanding yields under high input conditions (water and nutrients) were achieved by six Brazilian varieties grown in six planting dates and harvested at about 8, 11.5 and 15 months. High yields were explained by high but not excessive temperatures allowing the canopy to close after 73 days on average. Fresh cane yield accumulated on average at about 23 t/ha per month up to 8 months and then at about 10 t/ha per month thereafter. A new modeling feature was proposed to deal with the observed growth slowdown when the crop was about 8 months old and stalk dry mass yields were about 40 t/ha. This slowdown was attributed to a reduced growth phenomenon (RGP) discussed above (Sect 8.3). While a number of factors are thought to contribute to the RGP (Sect. 8.3) the new version of APSIM allows for RUE to be modified by leaf stage as a catchall for all RGP factors. Canopy parameters and slowdown factors linked to leaf stage were validated with independent experiments as well as with the original dataset used for developing the model. APSIM-Sugar now allows for reliable simulations in environments where high yields are expected. Despite the advances with these empirical slowdown coefficients, a mechanistic way to deal with RGP is still needed.

8.4.3 WaterSense

WaterSense was developed as a web-based irrigation scheduling system from concepts embodied in APSIM-Sugar and CANEGRO. The CANEGRO model was considered to be more reliable for representing the energy balance and APSIM the carbon balance (Inman-Bamber et al. 2005, 2006, 2007). WaterSense is no longer available as web service but the concepts are worth discussing here because of the benefits that were, and still can be obtained from combining concepts used in the two most widely applied modeling platforms for sugarcane. The concepts in WaterSense can also be easily adapted for use in other crops. Armour et al. (2013) showed how well drainage was simulated for both banana and sugarcane using WaterSense. Stokes et al. (2016) showed how WaterSense could be used to scale up from leaf to canopy in regard to CO_2 effects on stomatal resistance. Everingham et al. (2015) used this capability to for assessing climate change impacts on sugarcane in Australia.

In WaterSense, the development of the canopy, radiation interception, biomass accumulation and root water extraction are all based on concepts embodied in APSIM-Sugar. Potential transpiration is derived from reference evapotranspiration from FAO56 Penman-Monteith equation (Allen et al. 1998) and a crop factor (Kc) approach, similar to the recent version of the CANEGRO model. Evaporation from the soil surface is obtained from the amount of radiation reaching the soil surface and the water content of the top layer of soil (Armour et al. 2013).

The development of WaterSense in conjunction with farmers is an example of how research tools can be appropriated for end-users, provided the "technological frames" of developers and users overlap sufficiently after a "mutual" or "participatory action" learning process (Inman-Bamber et al. 2006; Webb et al. 2006; Jakku and Thorburn 2010). The outcome of the successful merging of technological frames for irrigation management during the development of WaterSense are now embodied in an active web service for sugarcane farmers in Australia provided by consultants (Wang et al. 2018a).

8.4.4 Model's Weaknesses

Historically, sugarcane models were developed on existing knowledge of crop physiology. It soon became evident that the knowledge available to account for available observations of crop growth, development, and yield was incomplete, and this led to an iterative process between field research and model building. For example, Lisson et al. (2005) acknowledged that crop aging processes, sucrose accumulation, water stress physiology, and the physiology of water retention in stalks, were important gaps for sugarcane at that time. Inman-Bamber et al. (2012) identified weaknesses in modeling the interaction between various drought resistance mechanisms. Some of these gaps have been filled at least to some extent; for example, Inman-Bamber et al. (2016) on drought resistance mechanisms and Dias et al. (2019) on aging. Knowledge gaps in water stress physiology have received more attention than other gaps in physiological knowledge because of the large influence of the water balance on crop production (Inman-Bamber and Jager 1988; Robertson et al. 1999a; Inman-Bamber and Smith 2005; Smit and Singels 2006; Singels et al. 2010b; Basnayake et al. 2012, 2015; Jackson et al. 2016; Marchiori et al. 2017; Zhao et al. 2017a). Generally, sugarcane models have been predicting Yw (rainfed conditions) quite well worldwide (see validations of Keating et al. 1999; Cheeroo-Nayamuth et al. 2000; Liu and Bull 2001, Inman-Bamber et al. 2001, 2016; Singels et al. 2008, 2010a; Sexton et al. 2014; Marin et al. 2015; Dias and Sentelhas 2017; Jones and Singels 2019).

O'Leary (2000) tested and reviewed three sugarcane models (APSIM-Sugar, CANEGRO and QCANE) regarding sucrose dynamics. This author proposed a (conceptual) process-based model that takes into account the dynamics between sucrose and reducing sugars and factors such as water, nitrogen, and temperatures stresses. Singels and Bezuidenhout (2002) improved the dry matter partitioning of CANEGRO regarding water stress and temperature, and suggested an interesting option to accommodate effects of nitrogen, variety differences, and ripener as well. Singels and Inman-Bamber (2011) proposed a process-based model that helped to understand genetic differences in sucrose accumulation and responses to water and temperature, by accounting for the differences in plant development and partitioning to structural components such as leaf and stalk fiber. Aging processes and lodging have received some attention in the literature (Park et al. 2005) and in improvements to some models such as CANEGRO (van Heerden et al. 2015) and APSIM-Sugar (Dias et al. 2019). Water retention in stalks remains as a weakness in current models and is an important issue because of its impact on costs of cane harvesting and transportation (Lisson et al. 2005).

Other important topics on sugarcane physiology for advancing our understanding and improving existing models are root dynamics and its role in crop yield-building processes, nutrients, flowering, and heat stress effects. Theoretical studies by Inman-Bamber et al. (2012) and Singels et al. (2016) with APSIM-Sugar and CANEGRO, respectively, indicated that roots are an important component for drought adaptation and that knowledge is limiting for modeling and understating adaptation to water stress. Studies by Chopart et al. (2008, 2010), Laclau and Laclau (2009) and Otto et al. (2011) provided valuable information for improved simulation of root profiles, penetration rate, and specific root length. This knowledge has not yet been used in models as far as we know.

While some models include a comprehensive nitrogen balance, the high nitrogen use efficiency found in Brazilian cropping systems (Robinson et al. 2011; Otto et al. 2016), particularly for plant cane (Franco et al. 2011), has not been well clarified. This is a topic that deserves attention because it could bring important insights for nitrogen management worldwide.

Sugarcane models do not currently simulate flowering even though flowering in favorable environments causes large losses in yield and quality worldwide. Simulation of this process would help in many applications such as determining yield potential, harvest management, varietal planning, and decision-making for chemical control.

Lastly, but not least, heat stress is expected to be an important crop constraint in tropical areas under changing climates where temperatures and heat waves are predicted to increase considerably. Temperature response functions in wheat and maize process-based models have been recently revised and improved for predicting yields in changing climates (Wang et al. 2017, 2018b). Jones and Singels (2019) made improvements in CANEGRO regarding temperature effects, but in other models this topic has received little attention.

The future of sugarcane models will also depend on advances and cooperation with genetics research, which has indeed already started for annual crops (Singels 2014). Simulations could indicate the desirability of traits (or QTL or genes) in target environments and thus help for ideotyping and breeding by design (Singels 2014; Hoffman et al. 2018).

Targeted experimentation and perhaps revisitation of existing experimental data to gain insight into sugarcane processes that still are poorly understood, such as crop slowdown with age, lodging, and roots-related and heat stress, will be needed.

8.5 Toward Sustainable Sugarcane Production: Usefulness of Process-Based Models Applications

Applications of sugarcane process-based models started in the beginning of 1990s with the development of CANEGRO (Fig. 8.3), ramping up considerably after CANEGRO's inclusion in the DSSAT platform in 1997 and 2008 (Figs. 8.5 and 8.6). During the end of 1900s and beginning of 2000s, APSIM-Sugar applications increased substantially with a peak of papers published in 2001 (Figs. 8.5 and 8.6).

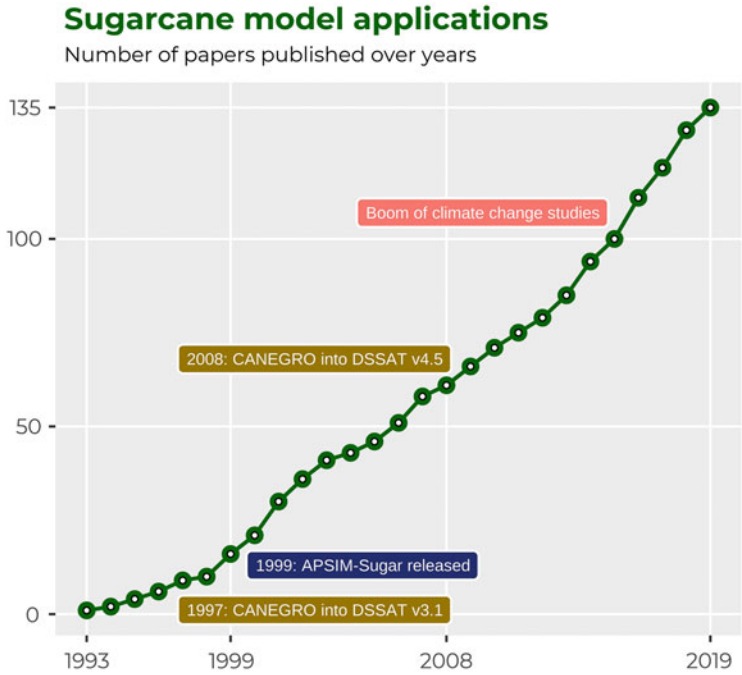

Fig. 8.5 Sugarcane process-based model application papers published over years

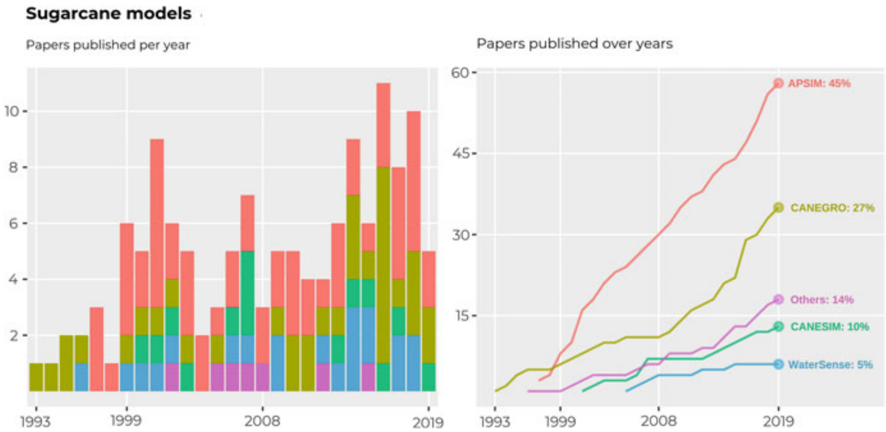

Fig. 8.6 Papers published per and over years categorized according to the main models

The second boom of the use of sugarcane models happened around 2007 and since then, modeling publications increased year by year, reaching other peaks in 2016 and 2018 (Fig. 8.5). Table 8.3 lists many of the referenced studies that employed sugarcane models we have found so far, categorized by the type of application. The

Table 8.3 List of various types of applications of the sugarcane models and example references that describe these applications in detail, organized by continent on which the studies were conducted. Participations, as a percentage of total number of papers, of each continent are shown in brackets

Continent	Application	References
Americas	Breeding support & variety comparison	Suguitani (2006), Leal (2016)
(22%)	Climate variability & change	da Silva (2012), Bello (2013), Singels et al. (2014), dos Vianna and Sentelhas (2014), de Carvalho et al. (2015), Marin et al. (2015), Jaiswal et al. (2017), Baez-Gonzalez et al. (2018), Sentelhas and Pereira (2019)
	Crop/Farm management	Galdos et al. (2009a, b) Brandani et al. (2015), de Oliveira et al. (2016)
	Fertilizer management	Costa et al. (2014), Marin et al. (2014), de Oliveira et al. (2016), de Barros et al. (2018)
	Water management & efficiency	dos Vianna and Sentelhas (2016), Costa (2017), Dias and Sentelhas (2018a)
	Yield benchmarking & gap	van den Berg et al. (2000), Marin et al. (2016), Dias and Sentelhas (2018b
	Yield forecasting	Pagani et al. (2017)
Asia	Breeding support & variety comparison	Bhengra et al. (2016)
(7%)	Climate variability & change	Jintrawet and Prammaneem (2005), Ahmad et al. (2016), Mishra et al. (2017), Ruan et al. (2018), Gunarathna et al. (2019)
	Water management & efficiency	Qureshi et al. (2002)
	Yield benchmarking & gap	Zu et al. (2018)
	Yield forecasting	Promburom et al. (2001), Piewthongngam et al. (2009),
Africa	Breeding support & variety comparison	Cheeroo-Nayamuth et al. (2003, 2011), Hoffman et al. (2018)
(32%)	Climate variability & change	Inman-Bamber (1994), Martiné et al. (1999), Cheeroo-Nayamuth and Nayamuth (2001), Walker and Schulze (2010), Knox et al. (2010), Black et al. (2012), Singels et al. (2018), Jones et al. (2014, 2015), Singels et al. (2014), Hoffman et al. (2017), Jones and Singels (2019)
	Crop/Farm management	Bezuidenhout et al. (2002), McGlinchey and Dell (2010), Paraskevopoulos et al. (2016)
	Drought adaptation	Singels et al. (2016)
	Fertilizer management	Thorburn et al. (2001b), Van Antwerpen et al. (2002), van der Laan et al. (2011)
	Water management & efficiency	Inman-Bamber et al. (1993), McGlinchey et al. (1995), Donaldson and Bezuidenhout (2000), Olivier and Singels (2001), Singels and Smith (2006), Kunz et al. (2014), Paraskevopoulos and Singels (2014), Singels et al. (2019)
	Yield benchmarking & gap	Inman-Bamber (1995), Cheeroo-Nayamuth et al. (2000, 2011), Singels (2007), van den Berg and Singels (2013), Jones and Singels (2015), Christina et al. (2019)

(continued)

Table 8.3 (continued)

Continent	Application	References
	Yield forecasting	Lumsden et al. (1998), McGlinchey (1999), de Lange and Singels (2003), Bezuidenhout and Singels (2007a, b), Martiné (2007), Morel et al. (2014a, b)
Oceania	Breeding support & variety comparison	Sexton et al. (2014)
(40%)	Climate variability & change	Lisson et al. (2000), Park et al. (2007), Park (2008), Webster et al. (2009), Biggs et al. (2013), Singels et al. (2014), Everingham et al. (2015)
	Crop/Farm management	McDonald and Lisson (2001)
	Drought adaptation	Inman-Bamber et al. (2012, 2016)
	Environmental pollution	Thorburn et al. (2001a, 2010, 2011), Webster et al. (2009), Armour et al. (2013), Biggs et al. (2013)
	Fertilizer management	(Keating et al. (1997), Thorburn et al. (1999, 2001b, 2003, 2004, 2017, 2018), Stewart et al. (2006), Park et al. (2010), Skocaj et al. (2013), Meier and Thorburn (2016), Zhao et al. (2017b), Kandulu et al. (2018)
	Land management	Mallawaarachchi and Quiggin (2001)
	Pest management	Liu and Allsop (1996)
	Water management & efficiency	Robertson et al. (1997, 1999b), Muchow and Keating (1998), Inman-Bamber et al. (1999, 2001, 2004, 2005, 2006), Attard et al. (2003), Everingham et al. (2002, 2008), Stoeckl and Inman-Bamber (2003), Lisson et al. (2003), Webb et al. (2006), Inman-Bamber and Attard (2008), An-Vo et al. (2019)
	Yield benchmarking & gap	Muchow et al. (1997b), Liu and Bull (2001)
	Yield forecasting	Everingham et al. (2002, 2005, 2007, 2009, 2016)

majority of model applications found employed APSIM-Sugar (45%) mostly in Australia, and CANEGRO plus CANESIM (a simpler version of CANEGRO) (37%) mostly in South Africa (Fig. 8.5). Use and applications of APSIM-Sugar and CANEGRO have increased in Americas in this decade, especially in Brazil (Table 8.3).

Water management and efficiency, nitrogen management, yield benchmarking, gap, and forecasting, and most recently climate change impact studies predominate in sugarcane model applications (Table 8.3 and Fig. 8.7). A common aspect in applications of models is the intrinsic effect of climate and its variability on production. Long-term climate series were employed in the majority of these studies. The following subsections provide some examples of model applications aimed at informing sustainable planning and decision-making processes in the sugarcane sector (Fig. 8.7).

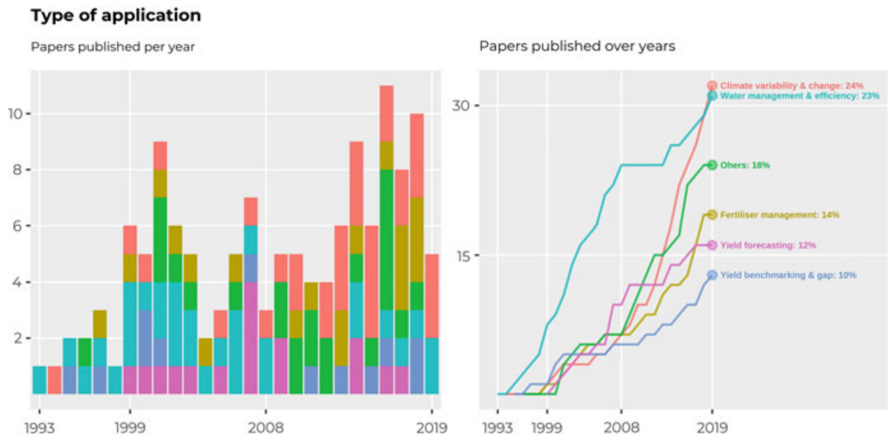

Fig. 8.7 Papers published per year and over years categorized according to the main types of application

8.5.1 Irrigation Management

Irrigation and its associated topics (for example, water allocation and water use efficiency assessment) are some of the most common areas of sugarcane model applications (Table 8.3). Examples are:

- Helping farmers with irrigation planning and management with web-based tools (McGlinchey et al. 1995; Inman-Bamber et al. 2005, 2007; Singels and Smith 2006; Inman-Bamber and Attard 2008), by coupling with seasonal climate forecasts (Everingham et al. 2002, 2008; An-Vo et al. 2019), or for new environments where little is known (Muchow and Keating 1998; Lisson et al. 2000; Inman-Bamber et al. 2006);
- Optimizing yields and making the best use of limited irrigation water (Inman-Bamber et al. 1999, 2007; Singels et al. 1999, 2019);
- Estimating drying-off days before harvest to optimize sucrose yields (Robertson et al. 1999b; Donaldson and Bezuidenhout 2000; Dias and Sentelhas 2018a);
- Dimensioning dam building for water storage (Lisson et al. 2003);
- Assessing risks of crop lodging considering irrigation strategies across varieties, environments, and growing months (Inman-Bamber et al. 2004; Paraskevopoulos et al. 2016).

Consultants are now using models to provide some of these irrigation applications as well as other services for sugarcane production (https://www.sqrsoftware.com/; http://agritechsolutions.com.au/).

8.5.2 Nitrogen Management and Its Implications to Environment

Nitrogen management is a particular topic that has been evaluated using sugarcane models (Table 8.3), mostly with APSIM-Sugar. Mechanization in sugarcane fields has increased in many areas worldwide, especially at harvesting, requiring adjustments in the cropping systems due to the residues left in the soil. Impacts of the green cane trash blanket on cane yield, soil components, and nitrogen fertilizer requirements have been assessed in Australia (Thorburn et al. 1999, 2001b, 2004; Meier and Thorburn 2016), South Africa (Thorburn et al. 2001b; Van Antwerpen et al. 2002) and Brazil (Costa et al. 2014; Marin et al. 2014; de Oliveira et al. 2016; de Barros et al. 2018) by using APSIM-Sugar.

Crop rotation with legumes to provide nitrogen through biological fixation is a practice that is recommended in many sugarcane cropping systems worldwide. Park et al. (2010) employed APSIM-Sugar to assess the impact of soybean rotation on nitrogen requirements in six sites (four of them in the Burdekin region) across Australia. Long-term simulations showed that nitrogen fertilizer could be reduced around 60–100%, 40–100%, 20–60%, 5–30% and $< 10\%$ for plant crops and the subsequent four ratoons, respectively, when compared to bare fallow systems. Their findings suggest a potential economic and environmental win–win outcome from refining and adopting sugarcane–legume rotation cropping systems in Australia and perhaps other countries.

Thorburn et al. (2017) simulated nitrogen management practices such as fertilizer rate, timing, and splitting, fallow management and tillage intensity with APSIM-Sugar across several sites in Australia and concluded that optimizing the application rate and fallow management should be prioritized for improving the nutrient efficiency. Thorburn et al. (2018) recently showed that rather than trying to improve nitrogen recommendations by changing concepts around target yields, the direct prediction of optimum nitrogen rates through the application APSIM-Sugar would be more beneficial for Australian environments, since the model captures soil and crop physiological processes, and their interactions with climate and management.

Environment implications of nitrogen fertilization can be also assessed through sugarcane models. Reducing impacts into the World Heritage listed Great Barrier Reef Marine Park from sugarcane farming is a particular concern in Australia. Sugarcane models (mainly APSIM-Sugar) have been applied to estimate nitrogen losses through runoff and leaching at several sites in the Australia Northeast region (Thorburn et al. 2003, 2011, 2017; Stewart et al. 2006; Armour et al. 2013; Biggs et al. 2013) and at Pongola, South Africa (van der Laan et al. 2011). Kandulu et al. (2018) integrated the APSIM-Sugar model with other techniques (probability theory, Monte Carlo simulation, and financial risk analysis) in a framework that allowed an assessment of economic and environmental trade-offs for nitrogen management strategies considering variable climatic and economic conditions. The framework was applied to a high rainfall production area close to the Great Barrier Reef in Australia. On average, net economic returns and nitrogen fertilizer rates were lowered when environmental costs were taken into account (Kandulu et al. 2018). This framework is interesting because it incorporates farmer risk behavior and environmental impacts, which in turn enhances the sustainability of a particular cropping system.

8.5.3 Yield Gap and Benchmarking

There are at least four approaches to estimate Yp and Yw and then to perform yield gap and benchmarking analysis; however, crop simulation models are recommended as a preference for such analyses, once they take into account the biological, biochemical, and biophysical aspects related to crop yield (van Ittersum et al. 2013).

Inman-Bamber (1995) first used CANEGRO to assess Yp and Yw (stalk and sucrose fresh mass yields) for 32 sites in South Africa considering two types of soils (a shallow loamy-sand and a deep structured one). These estimates were validated with variety trials, where variety NCo376 was common at 17 sites. Differences between Yp and Yw varied greatly depending on rainfall. In South Africa, irrigation is essential where Yw is less than 75% Yp. Years later van den Berg and Singels (2013) compared Yw estimates of CANESIM with Ya from small- and large-scale farmers using a CZ approach. Considering the period from 1988 to 2010, on average, Ya of large-scale farmers reached 77% of Yw, while for small-scale growers Ya stayed below 50% Yw. Factors such as damaging effects of a new pest (sugarcane thrips), inadequate nutrition and inadequate replanting, apparently linked to unfavorable socioeconomic conditions, were hypothesized to be the causes of the suboptimal production, revealing important points to be tackled by South African sugar industry.

Muchow et al. (1997b) demonstrated the remarkable variation in commercial sugar yields (Ya) across 14 sites along the Australian east coast and compared these to Yp using long-term APSIM-Sugar simulations. Maximum yields at four of these sites in some growing seasons were equivalent to Yp in less than 5% of the area harvested. District mean yields were 53–69% of Yp showing considerable room for improvement in the Australian sugar industry.

CANEGRO was used to develop norms for yield decline over successive ratoons in Swaziland (McGlinchey and Dell 2010). Yields tended to decline by about 1% for each successive ratoon in good soils but as much as 2.8% in poor soils. Ya/Yp for plant crops ranged from 0.81 to 0.90 depending on soil type.

Similar studies were performed using CANEGRO, APSIM-Sugar and other crop models in Mauritius (Cheeroo-Nayamuth et al. 2000, 2011), Brazil (Marin et al. 2016; Dias and Sentelhas 2018b), China (Zu et al. 2018) and Réunion (Christina et al. 2019). In Brazil, despite water being the factor that contributes most to cane yield gaps (Dias and Sentelhas 2018b), the gap attributed to general deficiencies in crop management, ranged from as low as 6 t/ha to as much as 79 t/ha depending on the region (Marin et al. 2016; Dias and Sentelhas 2018b).

Such analyses can help to quantify, identify the causes of, and mitigate yield gaps, in order to increase efficiency and consequently the production and sustainability of sugarcane industries worldwide. For instance, by increasing the national yield of Brazil on average by 10 t/ha (8.9 mi ha of crop area), an increment of 89 mi t would approach the total production of China (105 mi t) and Thailand (103 mi t) (Table 8.1). Such a vertical increase in production could meet future demands for sugarcane products (Marin et al. 2016) and relieve land use (Dias and Sentelhas 2018b) for other activities such as growing other crops or forest restoration in Brazil.

8.5.4 Yield Forecasting

Sugarcane and sugar yield forecasts are, or can be, useful for many agents involved in the sugarcane industries. Everingham et al. (2002), Higgins et al. (2007) and Bocca et al. (2015) provided examples of how forecasts can benefit planning and decision-making processes in the sugarcane industry. Sugarcane models can be used to generate the forecasts and two systems that are currently operating based on two models are briefly described below.

The CANESIM model is employed in an operational way in the South African sugar industry since 2000 and provides monthly yield forecasts for 48 CZs covering 14 mill supply areas. Further details can be found in Everingham et al. (2002) and Bezuidenhout and Singels (2007a, b). Basically, the system uses daily data from several automatic weather stations and completes the time-series with likely future weather conditions, to forecast yields for the pending harvest season, through model simulations at district, mill, and industry scales. Ten analog daily weather sequences are selected from past climate records, which best represent future weather conditions expected from ENSO indices provided by the South African Weather Service. Yields are represented as a percentage of those for the previous season. Forecasts are released monthly from November, 4 months before the start of the milling season (April to December), to September. Harvesting schedules and milling decisions are based on CANESIM forecasts, which are also used by South African Sugar Association as a support for planning and decision-making regarding sugar marketing.

TempoCampo is a recent yield forecasting system that is being developed for the Brazilian sugarcane industry and intended to extend the forecasts to other agro-industries (Marin 2017). The systems firstly used CANEGRO, but now is using the recently built SAMUCA model (Marin and Jones 2014), which relies on modeling approaches similar to those of CANEGRO and APSIM-Sugar. The system operates in a similar way to the South African one for supporting some mills in Southern Brazil.

Apart from the two systems presented previously, sugarcane models have been employed in studies worldwide together with other techniques, such as remote sensing (Morel et al. 2014a, b), statistics (Martiné 2007; Pagani et al. 2017) and data mining (Everingham et al. 2009, 2016). These all deserve attention for further development of integrated and operational yield forecasting systems for sugarcane industries worldwide.

Irrigation management, yield benchmarking, and yield forecasting are services based on the CANEGRO model that are offered by a commercial software developer (https://www.sqrsoftware.com/) providing many options for managing large and small sugarcane production systems in Africa, the Americas, and Australia (pers. com. Mark McGlinchey 2019).

8.5.5 Climate Change

Climate change is a huge concern of many societies globally, and this phenomenon will certainly influence sugarcane industries. Process-based crop models such as those previously discussed are preferred because they tend to include the effects of CO_2 increases that accompany warming, whereas statistical models typically do not (Lobell and Asseng 2017). Therefore, despite many approaches being used to assess climate change effects on the sugarcane crop/industry (Linnenluecke et al. 2018), only those with process-based sugarcane models are considered here. Studies involving this topic have increased substantially in the past few years (Tables 8.3 and 8.4).

The majority of climate change studies using crop models for sugarcane worldwide can be classified as impact studies (Table 8.4; Linnenluecke et al. 2018). The methodology varies considerably in regard to timeframe, future climate scenarios, type of global circulation models, downscaling, and other methods (Table 8.4; Linnenluecke et al. 2018), which makes comparisons difficult. Overall, the impact of climate change is predicted to be positive for sugarcane yields; however, it is also variable (Table 8.4). A recent assessment by Linnenluecke et al. (2019) has shown that sugarcane production in Australia of 1964–1995 compared to 1996–2012 has already been negatively affected by changes in climate variables, which reinforces the need for attention from policymakers and future research.

Sensitivity analyses, considering ranges for the main weather variables under changing climates (CO_2, air temperature, and rainfall), were performed for several sites worldwide mainly by using CANEGRO (Jones et al. 2014; Marin et al. 2015; Jones and Singels 2019). The simulations showed that sugarcane yields would, in general, be enhanced by changes in CO_2 and air temperature within the expected ranges predicted by IPCC (2014). Decreases in yields were predicted when rainfall was decreased within the expected ranges. Jones and Singels (2019) refined CANEGRO with regard to some plant processes, including CO_2 interactions and high temperature effects (see Sect. 8.4.1), and confirmed previous findings, except that the increments in yields were lower due to the inclusion of a more rational representation of the effect of temperature on sugarcane physiological processes.

Climate change adaptation studies using sugarcane models are scarce (Linnenluecke et al. 2018), but some can be found in literature. Cheeroo-Nayamuth and Nayamuth (2001) explored climate change adaptation strategies for sugar yields in Mauritius by using APSIM-Sugar, which included irrigation, cultivar and changes in harvest date. They concluded that irrigation was the best adaptive option depending on water availability, water storage, and cost. Park et al. (2007) used APSIM-Sugar to assess the adaptive strategy of changing planting dates in the most important growing regions in Australia. The simulations suggested that yield

Table 8.4 Climate change impacts studies on sugarcane crop using process-based crop models

Reference	Country (ies)	Model (version)	Climate baseline	Time frame	Emission scenarios	GCM or RCM	General impact
Cheeroo-Nayamuth and Nayamuth (2001)	Mauritius	APSIM-Sugar	MWD (1954–1996)	NA	Effect of CO_2 not considered	4 GCMs	–
Jintrawet and Prammaneem (2005)	Thailand	CANEGRO (3.5)	MWD (1986–1999)	2006–2024	720 ppm	CCAM model	+
Park et al. (2007)	Australia	APSIM-Sugar	NA	2030	Effect of CO_2 not considered	Ensemble of 12 GCMs and RCMs combined	+ or -
Webster et al. (2009)	Australia	APSIM-Sugar	NA	2030, 2070	425–449 ppm in 2030, 518–702 ppm in 2070	NA	+
Knox et al. (2010)	Swaziland	CANEGRO (4.0)	MWD (1980–2007)	2050	A2 and B2	HadCM3	+
Walker and Schulze (2010)	South Africa	APSIM-Sugar	–	2055	CO_2 effect on C_3 crop	NA	+
Black et al. (2012)	Ghana, Brazil	JULES	NCEP (1984–2008)	NA	345 ppm, 690 ppm	NA	+
Marin et al. (2013)	Brazil	CANEGRO (4.5)	MWD (at least 8 years between 1992–2007)	2050	A2 and B2	PRECIS, CSIRO	+
Biggs et al. (2013)	Australia	APSIM-Sugar	MWD (1957–2007)	2030	B1, A1B, A1FI	3 GCMs	+ or -
Bello (2013)	Colombia	AquaCrop	MWD (1994–2010)	2021–2030, 2041–2050	A1 and B2	3 GCMs	+
Jones et al. (2014)	7 countries	CANEGRO (4.5)	MWD (NA)	Sensitivity analysis			+

(continued)

Table 8.4 (continued)

Reference	Country (ies)	Model (version)	Climate baseline	Time frame	Emission scenarios	GCM or RCM	General impact
Singels et al. (2014)	South Africa, Australia, Brazil	CANEGRO (4.5)	MWD (1980–2010)	NA	734 ppm (A2)	3 GCMs from CMIP3	+
Marin et al. (2014)	Brazil	CANEGRO (4.5), APSIM-Sugar	MWD (1992–2007)	Sensitivity analysis			+
Marin et al. (2015)	Brazil	CANEGRO (4.5), APSIM-Sugar	MWD (NA)	Sensitivity analysis			+
Jones et al. (2015)	South Africa	CANEGRO (4.5)	MWD (1980–2010)	2040–2070	571 ppm	5 GCMs from CMIP5	+
de Carvalho et al. (2015)	Brazil	Century (v.5)	MWD (1950–2012)	3 future periods	A1B	Eta/CPTEC, HadCM3	–
Everingham et al. (2016)	Australia	WaterSense	AWAP (1970–2000)	2046–2065	B1 and A2 scenarios, with and without elevated CO_2	Ensemble of 11 GCMs from CMIP3	= or +
Jaiswal et al. (2017)	Brazil	BioCro	NCEP (1980–2010)	2040, 2050	494 ppm (2040), 540 ppm (2050)	5 GCMs	- or +
Ruan et al. (2018)	China	APSIM-Sugar	MWD (1961–2010)	3 future periods	RCPs 4.5 and RCP8.5	Ensemble of 28 GCMs from CMIP5	+
Singels et al. (2018)	South Africa	CANEGRO (4.7)	MWD (1971–1990)	2046–2065	NA	4 GCMs	+
Baez-Gonzalez et al. (2018)	Mexico	ALMANAC	MWD (1961–2010)	2021–2050	A2	10 GCMs	+
Jones and Singels (2019)	5 countries	CANEGRO (4.7)	MWD (1980/84–2008/10)	Sensitivity analysis			+

Based on Linnenluecke et al. (2018)
NA not available, found, or specified, *MWD* measured weather data from ground weather stations, *GCM* global circulation models, *RCM* regional circulation models

potential will increase marginally by the year 2030 if planting the date occurs earlier than is presently practiced in the south of the industry and later in the north.

8.5.6 Drought Adaptation and Breeding

Water deficit, caused by lack of or irregular distribution of rainfall throughout the sugarcane cycle, is one of the main causes of yield losses in sugarcane regions around the world (Inman-Bamber and Smith 2005; Basnayake et al. 2012; Dias and Sentelhas 2018b). Even for irrigated cropping systems, there is an increasing concern about the amount and efficiency of water use, owing to the rising costs of applying water, limited availability of water for irrigation, and environmental issues (Jackson et al. 2016) (see Sect. 8.5.2).

There is an increasing interest in breeding for crops grown in water-limited environments (Inman-Bamber et al. 2012). Inman-Bamber et al. (2012) employed APSIM-Sugar for a theoretical assessment aiming to find traits that could reduce the loss of sugarcane yield under rainfed conditions. Simulations showed that reduced root conductance or stomatal conductance would increase biomass yield in only about 5% in the driest climates on well-structured soils. Transpiration efficiency, a genotype-dependent trait (Saliendra and Meinzer 1992; Jackson et al. 2016), was also tested and an improvement in this trait arising from increased intrinsic water use efficiency would usually improve biomass under water deficit. Leaf and culm senescence were generally unsuccessful in conferring adaptation to water deficit.

In South Africa crop modelers are working together with breeders for sugarcane yield improvement. Ngobese et al. (2018) assessed traits for several varieties described in CANEGRO, to explore G × E interactions across environments and crop classes to assist in breeding efforts, according to the authors. Hoffman et al. (2018) predicted stalk dry mass yields reasonably well by estimating the RUE-related trait parameter in CANEGRO using leaf level photosynthesis and stomatal conductance measurements for several varieties, thus, showing that it is possible to apply crop models for helping sugarcane breeding.

8.6 Final Considerations

Sugarcane production is highly dependent on climate and its variability, and therefore also to climate change. Modeling groups and process-based models have been helping industries across the sugarcane producing regions worldwide, of which we can highlight irrigation management and yield forecasting as the most common applications. Possible climate change impacts are now quite well elucidated for some environments through model simulations, but studies focusing on adaptation strategies that minimize or even take further advantage of these impacts are necessary. Usefulness of sugarcane models in breeding started being demonstrated for South African and Australian programs. Nevertheless, there is room for improvements that were also discussed, many of which were previously acknowledged in the past. Continuous physiology experimentation and modeling efforts are needed to fill the knowledge gaps in these sugarcane research areas. Collaboration between research groups worldwide might speed up this process. Despite their weaknesses, sugarcane models are a powerful tool to understand and propose management and adaptive actions to mitigate losses or increase yields under current and future climates.

Acknowledgments This contribution was not funded by any institution. However, the first author (HBD) is truly grateful to the São Paulo Research Foundation (FAPESP), which facilitated his studies in sugarcane agrometeorology, physiology, and modeling in the past few years through the grants #2014/05173-3, #2016/11170-2, and #2017/24424-5.

Climate data used in Fig. 8.2 were obtained from the NASA Langley Research Center (LaRC) POWER Project funded through the NASA Earth Science/Applied Science Program.

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