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# Cultivating C4 crops in a changing climate: sugarcane in Ghana

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## Abstract

Over the next few decades, it is expected that increasing fossil fuel prices will lead to a proliferation of energy crop cultivation initiatives. The environmental sustainability of these activities is thus a pressing issue—particularly when they take place in vulnerable regions, such as West Africa. In more general terms, the effect of increased CO<sub>2</sub> concentrations and higher temperatures on biomass production and evapotranspiration affects the evolution of the global hydrological and carbon cycles. Investigating these processes for a C4 crop, such as sugarcane, thus provides an opportunity both to extend our understanding of the impact of climate change, and to assess our capacity to model the underpinning processes. This paper applies a process-based crop model to sugarcane in Ghana (where cultivation is planned), and the São Paulo region of Brazil (which has a well-established sugarcane industry). We show that, in the Daka River region of Ghana, provided there is sufficient irrigation, it is possible to generate approximately 75% of the yield achieved in the São Paulo region. In the final part of the study, the production of sugarcane under an idealized temperature increase climate change scenario is explored. It is shown that doubling CO<sub>2</sub> mitigates the degree of water stress associated with a 4 °C increase in temperature.

**Keywords:** biofuel, sugarcane, climate change, Ghana, crop

 Online supplementary data available from [stacks.iop.org/ERL/7/044027/mmedia](http://stacks.iop.org/ERL/7/044027/mmedia)

## 1. Introduction

As fossil fuel prices increase, energy crops will become an increasingly lucrative option for farmers. Exploring the long-term environmental consequences of such cultivation is therefore a high priority. This is especially the case for high water requirement crops like sugarcane, which may strain

vulnerable water resources (Shrivastava *et al* 2011). In the case of sugarcane, moreover, the significant investment in infrastructure required for the refinement and production of ethanol means that long-term environmental sustainability is essential to profitability.

This modelling study considers two regions, one in Brazil and the other in Ghana. Brazil has a well-established sugarcane industry that provides substantial employment and income (of the order of 1 million workers producing around 37% of the world's total ethanol used as fuel (ProForest 2009)). The economic importance of sugarcane production,



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and the availability of high quality agronomical data over several decades, have motivated several previous modelling studies (e.g. Cuadra *et al* 2012) on which this work builds.

The prospect of exporting biofuel technology from Brazil to Ghana, and eighteen other African countries (Ben Barka and Mlambo 2011) raises urgent questions about environmental sustainability and the capacity of energy crop cultivation initiatives to alleviate poverty. In particular, there is a pressing need for rigorous assessment of the delicate balance between yield, and hence profitability, irrigation, water resources and the livelihoods of local people.

Assessing the implications of sugarcane cultivation in Ghana is particularly urgent. In 2008, Brazil's agriculture research agency, Embrapa, opened an office in Accra, with the intention of helping Ghana to build up its nascent ethanol industry. Subsequently, in 2010, Brazil made a \$300 million investment in exporting Brazilian sugarcane cultivation and refinement technology to Ghana (Ben Barka and Mlambo 2011). This investment has led to a major sugarcane cultivation initiative, which will involve substantial development. It was recognized at the outset of this initiative that sugarcane cultivation in Ghana would require irrigation. In order to provide this irrigation from the River Daka, a dam is proposed.

The economic feasibility of growing sugarcane depends on the attainable yield, the operating costs for all parts of the ethanol production process, and the state of the bio-ethanol market. The costs of developing and maintaining infrastructure must also be factored in. This study aims to investigate two (physical environment) aspects of this complex issue: yield and irrigation requirement. Further studies are underway on the hydrological, environmental (e.g. water quality) and economic consequences of cultivating sugarcane in this region.

The success of cultivation of a particular crop in a certain region can be estimated with a crop model, in combination with agro-meteorological field studies and suitable driving data. The growing importance of sugarcane, both for sugar and biofuel, has motivated the development of a number of sugarcane specific models designed to simulate the partitioning of biomass to the different organs as the plant grows. These models include CANEGRO (Inman-Bamber 1991), APSIM-Sugarcane (Keating *et al* 1999) and QCANE (Liu and Bull 2001).

Sugarcane models have proved useful in several contexts—including scheduling irrigation (Singels and Smith 2006), predicting yield (Lisson *et al* 2000) and investigating the impact of sugarcane on agricultural emissions (Thorburn *et al* 2009). There are, however, no modelling studies of sugarcane cultivation in West Africa, despite its increasing importance as a cash crop in the Ivory Coast and Nigeria—as well as in Ghana (FAO 2012).

There have been, moreover, no detailed studies of the impact of climate change on sugarcane production, with only a few qualitative investigations reported in the literature (Gawander 2007), although studies of other crops have demonstrated that climate change may have a significant impact on yield (for example Jerry *et al* 2012; Parry

*et al* 2004). The response of agricultural production to high temperatures and elevated CO<sub>2</sub> is relevant both to the sustainability of specific initiatives (such as sugarcane in Ghana), and to the wider issue of plants' response to climate change. The latter affects the land surface carbon sink, water use and its efficiency, as well as future atmospheric concentrations of CO<sub>2</sub>—a critical issue within a socio-economic, as well as a scientific context (Mercado *et al* 2009, Qian *et al* 2010).

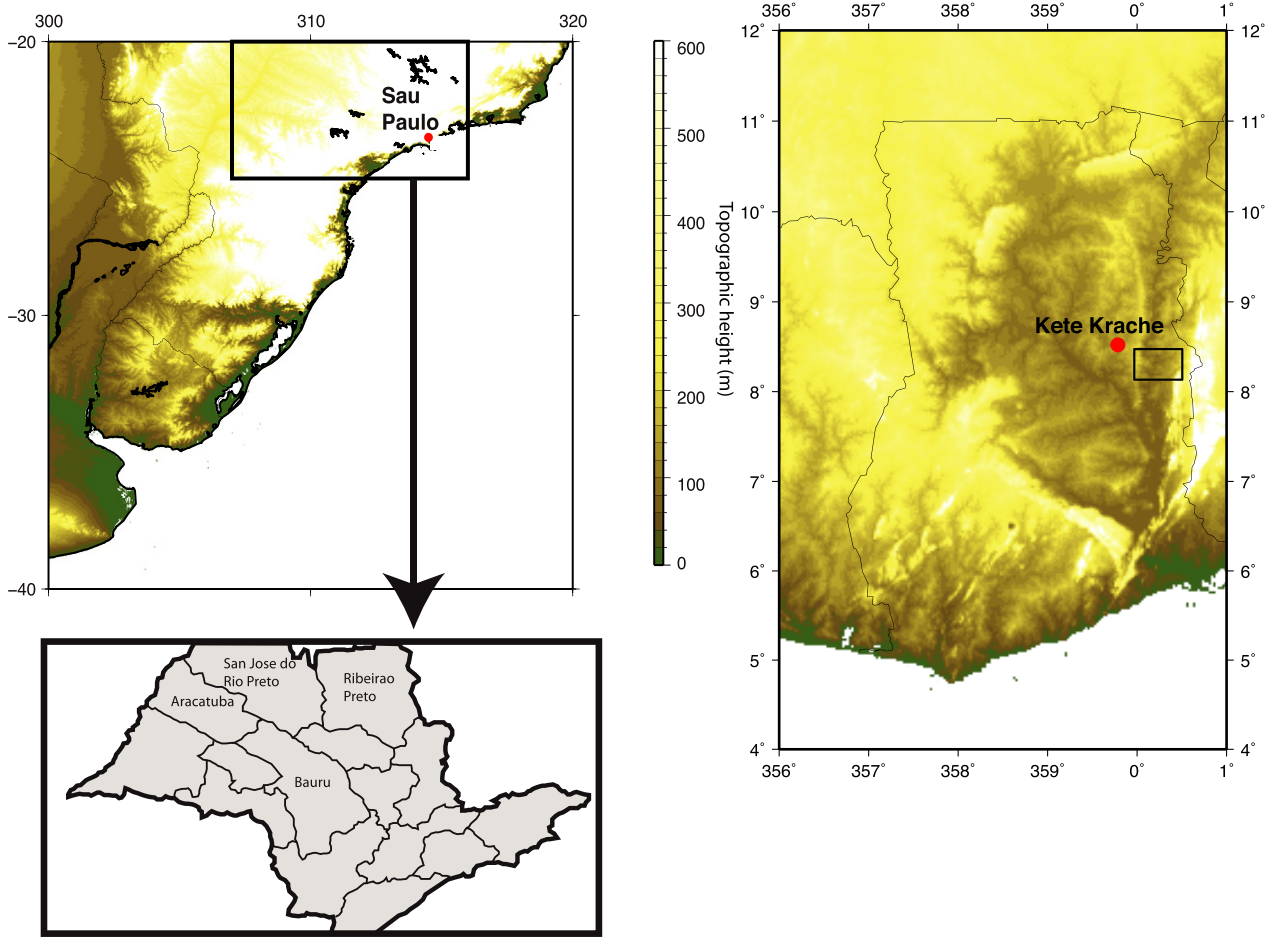
Under scenarios of climate change, in which both temperature and CO<sub>2</sub> are higher than the present day, there are competing effects on C4 plants, such as sugarcane. Higher temperatures increase soil and canopy evaporation, potentially reducing the soil moisture available to plants, while higher CO<sub>2</sub> levels reduce transpiration rates. In addition, up to the temperature optimum point, higher temperatures increase rates of both plant respiration and photosynthesis—with a somewhat greater impact on respiration (Cox *et al* 1998) (note that the temperature optimum point is not reached within the simulations carried out in this study). There is thus a tendency to reduced net primary production (NPP), and therefore, less accumulation of biomass, when temperatures are high (Valentini *et al* 2000).

There remain uncertainties about how these competing factors interact to determine the response of C4 vegetation to climate change (Hunt *et al* 1996, Markelz *et al* 2011, Vico and Porporato 2008). The model experiments carried out in this study aimed to investigate both the specific case of sugarcane cultivation in Ghana and the more general interplay between CO<sub>2</sub>, temperature and water stress for this crop, as relatively little research has been conducted on this topic.

In this study, we investigated sugarcane cultivation in the Daka River region of Ghana (see figure 1(b) for location). The focus was on irrigation requirements, which can be considered a metric of demand on the hydrological system—a key determinant of environmental sustainability.

In order to provide a long-term view, a process-based crop model was used to compute irrigation requirements both for present day climate conditions and for an idealized scenario in which the mean temperature is raised by 4 °C and CO<sub>2</sub> levels are doubled. This is in line with both the global and African climate sensitivities (Boko *et al* 2007)—the global climate sensitivity multi-model mean is estimated as 3 K ± 1.5 K (Pachauri and Reisinger 2007). The multi-model mean projected precipitation change for West Africa by the end of the 21st century under a business-as-usual scenario is a small increase (<5%) (Christensen *et al* 2007). There is considerable uncertainty in this estimate, with half the models projecting a precipitation increase and half projecting a decrease (Christensen *et al* 2007). Because of the large uncertainty in precipitation projections, and the small projected changes, we did not impose a precipitation change in the idealized scenario.

Sugarcane is not yet being cultivated in Ghana, so no yield data are available. For this reason, the model was evaluated for four meso-regions in the São Paulo state, for which annual yield data were available for 1990–2011 (see figure 1(a) for location).



**Figure 1.** Location and climate of the study areas in Brazil (a) and Ghana (b). The locations of the mean seasonal cycles of precipitation in figure 2 are shown as red circles. The Daka River region is shown as a rectangle on (b). The São Paulo meso-regions referred to in the text are shown as the zoomed rectangle on (a).

In summary, the first parts of this study consider the present day and ask, firstly, how well the model can represent sugarcane cultivation in the São Paulo region of Brazil. Once the model was validated, it was used to assess the irrigation requirement for sugarcane cultivation in Ghana, for the present day climate. The next part of the study considered a high temperature scenario (similar to the type of scenario design used in, for example, Schlenker and Roberts 2008). For the specific case of Ghanaian sugarcane, the crop model was used to assess how irrigation requirements would change in this scenario. In the final part of the study, the physiological mechanisms by which plants adapt to drought stress were investigated with the crop model. These results enabled us to infer the extent to which the drought stress, associated with higher temperatures, would be ameliorated by the higher levels of atmospheric CO<sub>2</sub> concentrations typically assumed under climate change scenarios.

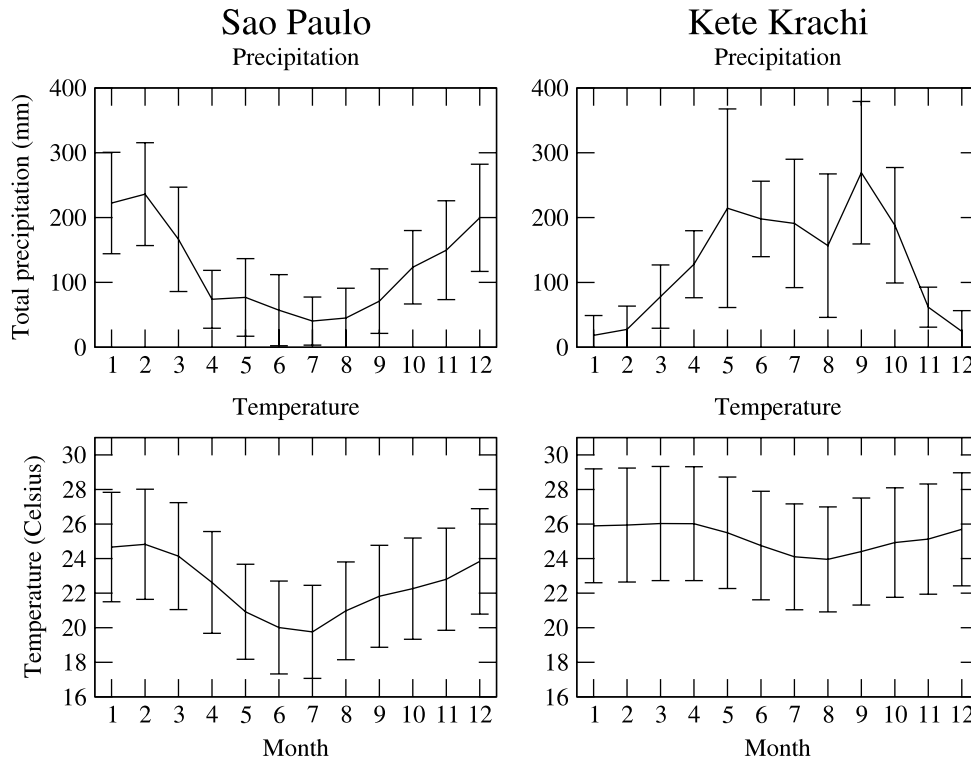
## 2. The study areas

As was summarized in section 1, this modelling study focused on two regions: the São Paulo State of Brazil and the Daka River region of Ghana (see figure 1 for locations). The annual

cycles of temperature and precipitation for Kete Krachi, a station near the Daka region, in Ghana and São Paulo in Brazil are shown in figure 2.

The annual mean totals of precipitation in both regions are similar (1556 mm for Kete Krachi and 1462 mm for São Paulo). Both regions also exhibit considerable interannual variability in precipitation (interannual standard deviations for annual total precipitation were 358 mm for Kete Krachi and 253 mm for São Paulo). From the point of view of crop cultivation, the most significant differences in the climates of the two regions are annual mean temperature and interannual variability in precipitation. The mean annual temperature in Ghana is significantly higher than in the São Paulo state, and shows less seasonal variability; while both the seasonal and interannual variability in precipitation is greater (figure 2). It is expected that in Ghana irrigation will be required to counteract the large variability in precipitation (see section 5 for sensitivity studies for different irrigation amounts), and a dam is proposed to accomplish this.

In addition to the climate, agronomic management practices, such as planting and harvesting date strongly affect yield. A sensitivity analysis for ratooning date was carried out for both Brazil and Ghana; it was found that for Brazil an



**Figure 2.** Seasonal cycle in precipitation and temperature for Kete Krachi and Sao Paulo (locations shown in figure 1). Temperature data are gridded data from the NCEP reanalysis and precipitation are gauge data from the Global Historical Climate Network dataset—time span 1961–90. Error bars are the interannual standard deviation.

August sowing date, and for Ghana a November sowing date gives the highest yield. This is in line with established practice in the São Paulo state of Brazil and planned practice in Ghana (Cuadra 2010).

### 3. Modelling methodology

In this study, the Joint UK Land Environment Simulator (JULES) land surface model was adapted to simulate the growth of sugarcane, using the carbon partitioning formulations from CANEGRO. The approach used was similar to that adopted in a study by Cuadra *et al* (2012) who incorporated the carbon partitioning formulations from CANEGRO into Agro-IBIS, which is a well-established process-based land surface/dynamic crop growing model, involving below-ground and above-ground, energy, water and carbon budgets (see Foley *et al* 1996, Kucharik and Brye 2003 for a detailed description); this model has been tested for a range of crops—for example maize in the US (Kucharik 2003).

Further detail on JULES-SC (where SC stands for sugarcane) is given in the supplementary information (available at [stacks.iop.org/ERL/7/044027/mmedia](http://stacks.iop.org/ERL/7/044027/mmedia)). The following gives an overview of the most relevant parameterizations and physical processes for this study.

Sugarcane assimilates carbon through the C4 photosynthetic pathway. There is abundant observational evidence that production of biomass by C4 plants is increased by rising concentrations of CO<sub>2</sub>—especially under water-stressed

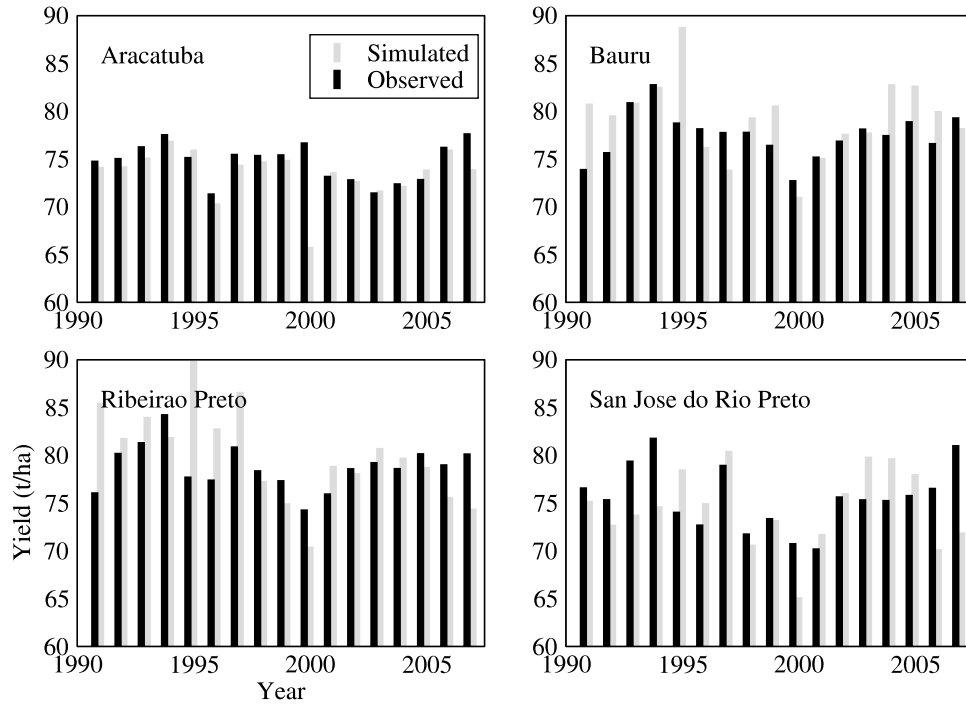
conditions (Leakey 2009). This is likely to be primarily because of the impact of CO<sub>2</sub> concentrations on transpiration and hence on water use efficiency (WUE). Specifically, when CO<sub>2</sub> concentrations are raised, fewer stomata need to be open in order to maintain optimal CO<sub>2</sub> levels within the plant, which leads to a reduction in the rate of transpiration (Collatz *et al* 1991—on which the C4 parameterizations of the JULES model, used in this study, are based). For given meteorological conditions, the plant will therefore lose less water to the atmosphere—and hence have greater WUE. Hence, over the course of a growing season, the plant will be less stressed and accumulate more biomass (Ghannoum *et al* 2000, Markelz *et al* 2011).

The surface fluxes of moisture and heat in JULES depend on the atmospheric boundary conditions and the characteristics of the land surface. The fluxes are computed by a network of parameterizations including soil surface, stomatal and aerodynamic conductances. Stomatal conductance also controls the intake of CO<sub>2</sub>, and is thus the link between the carbon, water and energy cycles. The stomatal conductance parameterization (Clark *et al* 2011, Cox *et al* 1998) depends on environmental conditions, including the ambient concentration of CO<sub>2</sub>. Specifically, stomatal conductance is parameterized as:

$$g_c = \frac{aA_c}{c_a} \tag{1}$$

where  $g_c$  is stomatal conductance ( $m\ s^{-1}$ ),  $A_c$  is net canopy photosynthesis rate ( $\mu mol\ m^{-2}\ s^{-1}$ ),  $c_a$  is the atmospheric





**Figure 3.** Observed and simulated yield time series for meso-regions in Brazil (locations indicated on the map).

concentration of CO<sub>2</sub> (μmol m<sup>-3</sup>) and *a* is a calibration factor (Cox *et al* 1998).

This parameterization means that under conditions of higher CO<sub>2</sub>, stomatal conductance is reduced, which for given climate conditions will reduce evapotranspiration:

$$E = D\rho g_c \tag{2}$$

where *E* is evapotranspiration (g m<sup>-2</sup> s<sup>-1</sup>) *D* is the humidity deficit (g kg<sup>-1</sup>),  $\rho$  is surface air density (kg m<sup>3</sup>). The humidity deficit is defined as:

$$D = q_{\text{sat}}(T)(1 - RH) \tag{3}$$

where  $q_{\text{sat}}(T)$  is the saturated specific humidity at the temperature *T* (g kg<sup>-1</sup>); *RH* is the relative humidity.

JULES calculates the photosynthesis rate using the method described in Collatz *et al* (1991), for the C3 pathway and Collatz *et al* (1992), for the C4 pathway. Potential photosynthesis takes place at the minimum of three limiting rates: light; enzyme kinematics (Rubisco); and the transport of photosynthetic products. The potential photosynthesis is reduced under water-stressed conditions by the soil moisture availability factor (referred to as  $\beta$ ), which represents the fraction of soil moisture available to plants.

$$\beta = \begin{cases} 1 & \theta \geq \theta_c \\ \left[ \frac{\theta - \theta_w}{\theta_c - \theta_w} \right] & \theta_w < \theta < \theta_c \\ 0 & \theta \leq \theta_w \end{cases} \tag{4}$$

where  $\theta$  is the volumetric soil moisture concentration (m<sup>3</sup> m<sup>-3</sup>),  $\theta_w$  is the volumetric soil moisture concentration at the wilting point—i.e. when photosynthesis and transpiration cease, and the plant dies (m<sup>3</sup> m<sup>-3</sup>) and  $\theta_c$  is the volumetric

soil moisture concentration at the critical point, which is the level at which plant water stress starts (m<sup>3</sup> m<sup>-3</sup>).

It can be clearly seen that under these parameterizations, increasing CO<sub>2</sub> concentrations in the atmosphere may lead to higher photosynthesis by reducing stomatal conductance and thus evapotranspiration with a consequent increase in soil moisture content—and hence photosynthesis. It is clear from the formulation of  $\beta$  that this increase in photosynthesis rate is, however, unlikely to occur under all conditions. For example, very high rainfall/low temperatures may maintain  $\beta$  at 1.0 (because  $\theta > \theta_c$ )—even if stomatal conductance, and hence transpiration, is high.

Photosynthesis is scaled from the leaf to the grid box scale by treating it as a function of leaf area index (LAI) (Sellers *et al* 1996). Part of the carbon assimilated during photosynthesis (the gross primary productivity (GPP)) is converted to energy for maintenance of the existing vegetation and growth (i.e. respiration). The biomass generated (net primary productivity (NPP)) is the difference between the GPP and autotrophic respiration.

#### 4. Evaluation of the JULES-SC model for Brazil

Performance of JULES-SC was assessed by comparing the simulated sugarcane yield with observations for the four São Paulo meso-regions shown in figure 1. The model is forced with meteorological variables provided by a gridded dataset designed for driving land surface models (see supplementary information available at [stacks.iop.org/ERL/7/044027/mmedia](http://stacks.iop.org/ERL/7/044027/mmedia)). Figure 3 shows simulated and observed yield for all four meso-regions (data were collected by the governmental institution IBGE (Brazilian Institute of

Geography and Statistics—[www.sidra.ibge.gov.br](http://www.sidra.ibge.gov.br)). It can be inferred from figure 3 that the model captures the most crucial aspects of both the observed spatial and interannual variability. In both the observations and the model the highest yields occurred in the Ribeirão Preto meso-region (mean simulated yield 82 t ha<sup>-1</sup>; mean observed yield 79 t ha<sup>-1</sup>) and the lowest in the Araçatuba region (mean simulated yield 72 t ha<sup>-1</sup>; mean observed yield 71 t ha<sup>-1</sup>).

Although the model captures mean yield well, its skill in reproducing the interannual variability varies between meso-regions. Furthermore, the simulated interannual variability in yield is consistently greater than that observed (4.63 t ha<sup>-1</sup> compared with 2.427 t ha<sup>-1</sup> observed in Ribeirão Preto, for example). The correlation between observed and simulated yield is highest for Araçatuba (correlation coefficient,  $r^2$ , of 0.61), and lowest for Ribeirão Preto ( $r^2 \sim 0$ —although this increases to 0.43 for the later part of the time series (1995–2008)). The other two regions, São Jose do Rio Preto and Bauru, have  $r^2$  values of 0.41 and 0.38, respectively.

The model's reasonable ability to capture the spatial variability and mean yields indicates that it is capable of representing the gross response of sugarcane to variations in climate and soil type. However, these simulations do not include irrigation, fertilizer application or soil management—all of which can affect interannual variability in the yield. Unfortunately these management practices are very difficult to incorporate reliably in biophysical land surface models, largely because dependable data are simply not available. In general, it is likely that farmers have become skilled at adapting agronomical practices to mitigate interannual variability. This observation is consistent with the excessively high simulated interannual variability, especially in the earlier parts of the time series. This suggests that the lack of model skill in representing interannual variability primarily arises from omission of management practices from JULES-SC—rather than from problems with formulation of the model itself.

The question arises as to whether JULES-SC is suitable for simulating sugarcane cultivation in Ghana—a critical question, since there are no yield data to test the model directly in the region. Section 2 described how Ghana's climate differs from Brazil's. This does not, however, bear on the credibility of our simulations. As was described in the methodology, and supplementary information sections (available at [stacks.iop.org/ERL/7/044027/mmedia](http://stacks.iop.org/ERL/7/044027/mmedia)), JULES-SC is built on a process-based land surface model (JULES). JULES has been tested against observations for many regions around the globe, including Africa, both in its offline mode and as the land surface scheme of the Hadley Centre climate models (Blyth *et al* 2011, Clark *et al* 2011, Ghent 2010 and references therein).

The sugarcane parameterization included in JULES does not significantly alter the basic energy and water balances, which ultimately control biomass production (see supplementary information available at [stacks.iop.org/ERL/7/044027/mmedia](http://stacks.iop.org/ERL/7/044027/mmedia)). It is evident therefore that JULES-SC is capable of (i) simulating biomass production in both Brazil and Ghana and (ii) simulating the partitioning of biomass to

**Table 1.** Irrigation, CO<sub>2</sub> and temperature scenarios for the JULES-SC integrations. See text and supplementary information (available at [stacks.iop.org/ERL/7/044027/mmedia](http://stacks.iop.org/ERL/7/044027/mmedia)) for further details for how these were set up.

Set	Meteorology	Irrigation	CO <sub>2</sub> concentration (ppm)	Period
1	Present day	0–10 mm	345	1984–2008
2	High temp	0–10 mm	345	1984–2008
3	High temp	0–10 mm	690	1984–2008
4	Present day	0, 2.5, 5	66–690	1984–2008
5	High temp	0, 2.5, 5	66–690	1984–2008

the sugarcane plant organs during its development. This lends credence to the Ghana simulations.

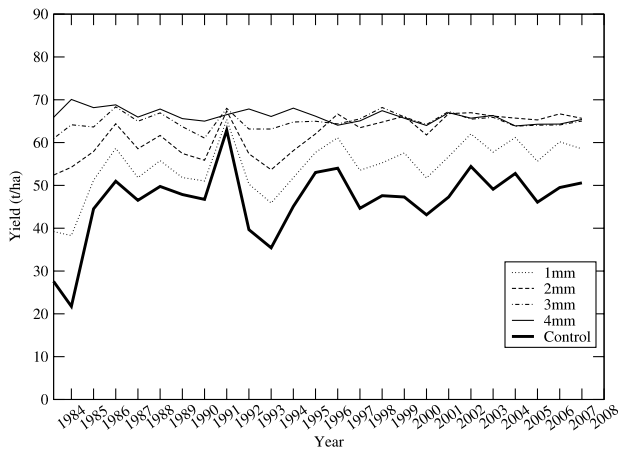
## 5. Sugarcane cultivation in Ghana under present day and high temperature conditions

Unlike Brazil, Ghana cannot rely primarily on rain-fed agricultural practices. In order to assess the long-term sustainability of sugarcane in Ghana, this study investigated the interplay between CO<sub>2</sub> concentration, temperature and irrigation requirement. Irrigation was simulated by adding values to the precipitation time series simulating the sprinkle irrigation planned for the Daka river sugarcane plantations. Because evaporation and runoff are explicitly computed within the model, the irrigation amounts referred to here can be considered to be gross rather than net.

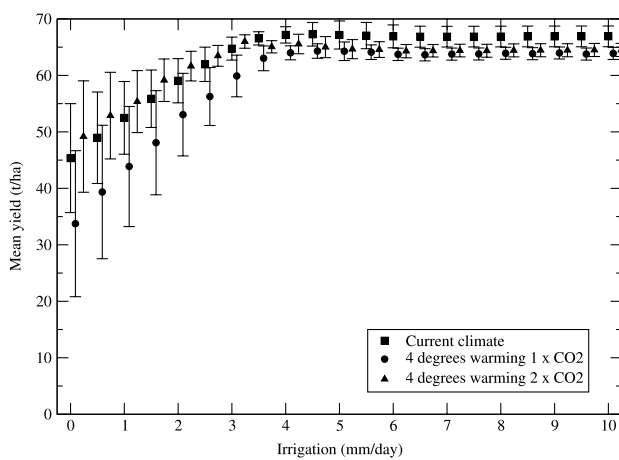
Present day yield, and changing irrigation requirement, were investigated through series of model integrations over the period 1984–2008. The interplay between atmospheric CO<sub>2</sub> concentration, drought stress and plant physiological processes was then explored in more depth through a further set of integrations in which CO<sub>2</sub> concentration was varied from 20% to double present day levels.

Figure 4 shows simulated yields of sugarcane for the Daka River region of Ghana in the present day climate for values of 0–4 mm d<sup>-1</sup> of irrigation (results from model integration set (1), see table 1). When there is no irrigation, the annual yield ranges from 22 to 61 t ha<sup>-1</sup>—reflecting the impact of water stress in low rainfall years. In all years, yield is increased by irrigation, which indicates that even in the highest rainfall years, sugarcane experiences some degree of water stress. The level of irrigation required to eliminate water stress is indicated by the point at which the interannual variability in yield virtually disappears (reflecting a lack of dependence on rainfall). It can thus be inferred from figure 4 that, under present day conditions, between 3 and 4 mm d<sup>-1</sup> of irrigation ensures that yield is not restricted by water stress. It should be noted however, that, in reality, this level of irrigation would not be required throughout the season and that irrigation can be adjusted depending on soil moisture levels. Moreover, some degree of water stress is desirable as the harvest date approaches, in order to maximize the partitioning of sucrose (for example Inman-Bamber 2004; Singels *et al* 2000).

The finding that yield is increased by irrigation is consistent with figure 5, in which mean yield is plotted against



**Figure 4.** Simulated historical sugarcane yield for the Daka River region of Ghana under a series of irrigation regimes.

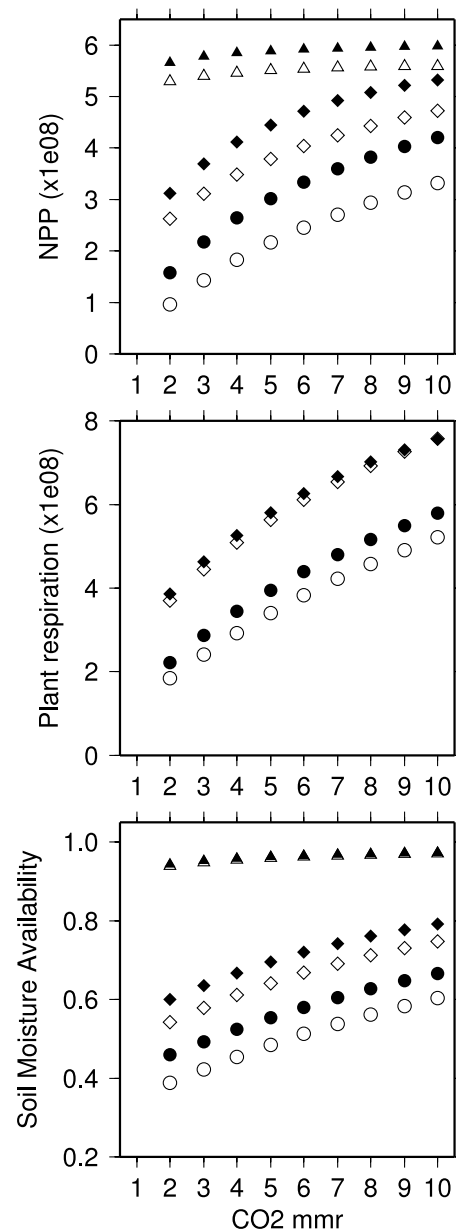


**Figure 5.** Irrigation versus mean yield for current climate, 4° warming with present day CO<sub>2</sub> and 4° warming with doubled CO<sub>2</sub>. The error bars represent the interannual standard deviation in yield.

irrigation. The error bars represent the interannual standard deviation (results from integration sets (1)–(3)). The reduction in interannual standard deviation and increase in mean yield with increasing irrigation is clear—with the curve plateauing at around 3.5 mm d<sup>-1</sup> when the mean yield reaches 65 t ha<sup>-1</sup>.

Figure 5 also illustrates the interplay between CO<sub>2</sub> concentration and temperature increase. When there is no irrigation, and CO<sub>2</sub> is set at present day levels (table 1, sets (1) and (2)), yield is markedly reduced in the high temperature scenario. When irrigation is introduced, however, the yields reach a similar level to those simulated under present day conditions. The irrigation required for set (2) is around 20% higher than in present day conditions—suggesting that the sugarcane is more water stressed when the temperature is high.

Increasing the concentration of CO<sub>2</sub> in the atmosphere counteracts this increased water stress. When CO<sub>2</sub> is doubled, the interannual standard deviations at all levels of irrigation are similar to those in the present day climate. When irrigation is over 5 mm d<sup>-1</sup>, the two high temperature scenario

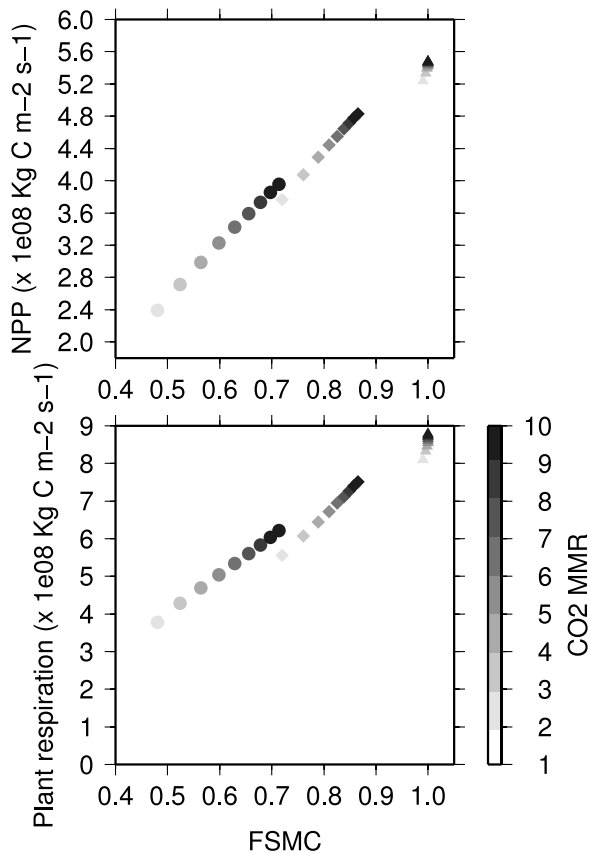


**Figure 6.** Mean annual NPP, respiration rate and soil moisture availability factor plotted against CO<sub>2</sub> concentration for model integrations of the Daka River region under sugarcane cultivation. Circles denote no irrigation and diamonds denote irrigation at 5 mm d<sup>-1</sup>. Filled shapes are for observed climate; unfilled shapes are for an idealized scenario, in which the temperature is warmed by 4 °C.

integration sets (i.e. (2) and (3)) are indistinguishable. It can also be seen that at these levels of irrigation, the yield in the high temperature scenarios, for this region, is consistently slightly lower than for the current climate.

In figure 6, NPP, total respiration rate and beta for the Daka valley region were plotted against ambient CO<sub>2</sub> concentration for un-irrigated/well-irrigated scenarios and high/present day temperature (integration sets (5) and (6)). Consistent with figure 5, NPP is increased by irrigation and reduced by high temperatures. When there is no irrigation, the decrease in NPP in the high temperature scenarios ((2) and





**Figure 7.** Mean NPP (top) and plant respiration rate (bottom) plotted against the soil moisture availability factor (FSMC) for model integrations with no irrigation (circles), 2 mm d<sup>-1</sup> irrigation (diamonds) and 5 mm d<sup>-1</sup> irrigation (triangles) under the present day climate for varying CO<sub>2</sub> concentration (indicated by the shading).

(3)) can be attributed to soil moisture stress. This is not the case for the high/present day temperature well-irrigated scenarios, which have indistinguishable near-one mean  $\beta$ -values (negligible water stress). Instead, the reduced NPP (and hence yield in figure 5) in the well-irrigated, increased temperature scenario is related to a significantly increased plant respiration rate. This effect is likely to be underestimated by JULES, which only simulates the temperature dependence of leaf maintenance respiration (maintenance respiration of the other plant organs is not temperature dependent; growth respiration is assumed to be 25% of photosynthesis at all temperatures).

The interaction between soil moisture and biomass accumulation is explored further in figure 7, in which NPP and plant respiration are plotted against the soil moisture availability factor  $\beta$  for all the CO<sub>2</sub> scenarios (integration set (5)). Figure 7 shows that, to a first order, NPP is proportional to soil moisture availability (consistent with figures 6 and 7).

## 6. Summary and discussion

A new sugarcane model, based on a well-established sugarcane model (CANEGRO) and land surface scheme

(JULES), has been evaluated against observations. The model has skill in replicating both the spatial and temporal variability in sugarcane yield in Brazil. The model was applied to the Daka River region of Ghana, where sugarcane cultivation is planned. In a high temperature scenario, if CO<sub>2</sub> is maintained at present day levels, sugarcane it would be expected that more irrigation would be required due to potential water stress induced by higher evapotranspiration rates. In this case study, a doubled CO<sub>2</sub> concentration limits the water stress induced by a concurrent 4 °C temperature increase so that yields comparable to present day levels can be achieved. The sensitivity of yields to higher temperatures and levels of CO<sub>2</sub>, as well as irrigation practice, was explored—both as a first step to investigating the long-term sustainability of sugarcane production and as a means of exploring the representation by JULES of the interplay between CO<sub>2</sub> concentration, water stress and photosynthesis in C4 plants.

According to the model experiments carried out in this study, given sufficient irrigation, it is possible to grow sugarcane in the Daka River region of Ghana, with a yield approximately 75% (when >3.5 mm d<sup>-1</sup> irrigation is applied) of that in southeast Brazil (with no irrigation). In both cases, it is assumed that plant growth is not limited by the nutrient content of the soil. The fact that sugarcane yields in northeast Brazil (Alagoas State, which is ~9°S as compared to ~8.5°N for the Daka River study area), which has a similar climate to our Ghanaian study region, are close to those predicted for Ghana (~60 t ha<sup>-1</sup> under irrigation), adds credence to these findings.

This modelling study was investigating a specific scenario, in which sugarcane growing technology (including sugarcane variety) is exported, *in toto*, from Brazil to Ghana. For this reason, the sugarcane cardinal temperatures for the Ghanaian crop were chosen to be the same as for the Brazilian crop. It should be noted, however, that even though the yield for the sugarcane grown in Ghana is relatively low, the partitioning to sucrose is expected to be high. This is because of the preferential partitioning to sucrose when the plant is water stressed (Singels *et al* 2005, 2011, van Heerden *et al* 2010). The model’s finding that sugarcane crops in Ghana are likely to be water stressed, unless irrigated, is thus a positive one, in this sense.

In the final part of this study, an idealized high temperature scenario was imposed. The high and observed temperature scenarios were implemented for a range of irrigation practices—both with and without changed CO<sub>2</sub> concentration. This series of experiments enabled us to investigate the interactions between soil water stress, temperature and CO<sub>2</sub> concentration. The results illustrate that under high temperatures, elevated CO<sub>2</sub> decreased stomatal conductance and hence reduces transpiration. An increase in atmospheric CO<sub>2</sub> concentration increases the WUE of the crop. This means that an increased CO<sub>2</sub> concentration could mitigate the water stress associated with temperature increase, and allow the crop to sustain its growth.

These findings are broadly consistent with experimental studies, which report that (i) elevated CO<sub>2</sub> improves drought tolerance of C4 crops, and (ii) if C4 plants are not drought

stressed, photosynthetic rates are not significantly affected by elevated CO<sub>2</sub> (Bunce 2004, Kim *et al* 2007, Leakey 2009, Markelz *et al* 2011). Even in observational studies, however, the exact nature of the physiological response of C4 vegetation to increases in CO<sub>2</sub> and temperature is not well understood (Ghannoum *et al* 2000, Bounoua *et al* 1999). Nevertheless, our study suggests that, under anthropogenic increases in temperature, the physiological response of some C4 plants to increased levels of CO<sub>2</sub> effectively compensates for the increased potential evapotranspiration.

The significance of these results extends beyond the sustainability of sugarcane cultivation in Ghana. Although C4 plants currently cover a far smaller fraction of the globe than C3 plants, and have a weaker immediate response to increases in CO<sub>2</sub>—understanding their response to climate change is critical. Using a model to study the growth of an irrigated crop under a range of temperature and CO<sub>2</sub> scenarios has provided a valuable opportunity to investigate this hypothesis.

In conclusion, as was explained in section 1, this study has only investigated one aspect of the feasibility of sugarcane cultivation in Ghana. The level of yield that would be profitable in Ghana depends on the operating costs for all parts of the ethanol production process; the cost of developing and maintaining the infrastructure required (possibly including damming the River Daka); and the bio-ethanol market. Studies are currently being carried out on the environmental, hydrological and economic consequences of growing irrigated sugarcane in the Daka River region of Ghana.

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