Geo-Eco-Trop., 2019, 43, 3, n.s.: 317-326

GEO - ECO - TROP
http://www.geoecotrop.be

Numéro spécial

Estimation of present and future soil water balance and its impacts on wheat yields in African regions north of the equator using a dynamic vegetation model

Estimation des bilans hydriques des sols présent et futur ainsi que de leur impact sur les rendements du blé dans les régions d'Afrique au nord de l'équateur à l'aide d'un modèle de végetation dynamique

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Résumé : Le réchauffement climatique et la croissance démographique menacent l'agriculture et la sécurité alimentaire en Afrique. Dans ce contexte, le modèle de végétation dynamique CARAIB est utilisé sur les régions d'Afrique situées au nord de l'Equateur pour évaluer le bilan hydrique des sols dans le futur et l'impact sur les rendements du blé (une culture dont la distribution pourrait rapidement augmenter sur le continent en raison de la forte demande). Forcé avec différents scénarios climatiques et de concentrations en CO_2, l'incertitude sur les projections de rendements est grande. Présumant un effet du CO_2, les résultats du modèle indiquent que la stimulation de la croissance du blé par le CO_2 devrait surpasser les impacts négatifs du climat avec des augmentations de rendement de l'ordre de 20 % dans les régions subsahariennes au-dessus de l'équateur. Sans l'effet de fertilisation, le modèle projette des diminutions de rendement causés par le réchauffement et l'assèchement des sols. Comme l'adaptation des pratiques agricoles en Afrique est aussi une inconnue, l'effet de l'irrigation est aussi analysée.

Mots-clés: rendement du blé, changements climatiques, sécheresse, irrigation, Sahel, Maghreb.

Abstract : Climate warming and growing population are hot topics for agriculture and food security in Africa. In this context, the CARAIB dynamic vegetation model is run over Africa north of the equator to project future soil water balance and its impact on yields of wheat (a culture whose distribution is projected to increase rapidly given the huge demand on the continent). Forced with different climate and CO_2 concentration scenarios, the uncertainties in yield projections are large. Assuming CO_2 effects, model results indicate a potential stimulation of wheat growth overcoming negative climate change impacts with yield gains around 20 % in sub-Saharan regions above the equator (up to 40 % in Eastern Africa). Without CO_2 fertilization, negative yield anomalies are projected under future climate trends (warming and drying). Since the agronomic adaptation of African agriculture is an important source of uncertainties, the yield-increasing effect of irrigation is also analysed.

Keywords: wheat yield, climate change, drought, irrigation, Sahel, Maghreb.

INTRODUCTION

Climate change is affecting agriculture all over the world with dramatic consequences in developing countries already vulnerable owing to limited water and food resources. Without adaptation, climate warming is projected to have negative effects on yields for the major crops (wheat, rice, maize and soybean) in both tropical and temperate regions (PORTER *et al*., 2014). Numerous studies already highlight the negative response of crop yields to climate trends over the last thirty years; these losses being so far largely offset at global scale by technological yield gains made over the same period (LOBELL & FIELD, 2007; ASSENG *et al*., 2015; LOBELL *et al*., 2011). Each degree-Celsius increase in global mean temperature would reduce on average (with regional increases or decreases) global wheat production by 6.0 %, rice by 3.2 %, maize by 7.4 %, and soybean by 3.1 % (ZHAO *et al*., 2017). With or without adaptation, negative impacts on average yields become likely from the 2030s with median yield impacts of 0 to -2 % per decade projected for the rest of the century (PORTER *et al*., 2014). These impacts occur in the context of world population growth and associated rising crop demand,

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which is projected to increase by about 14 % per decade until 2050 (ALEXANDRATOS & BRUINSMA, 2012).

Situations being highly dependent on crop and geographical region, the present study focuses on wheat in African regions north of the equator. Wheat is the most abundant crop, occupying 22 % (400 million ha) of the total cultivated area in the world (LEFF *et al*., 2004) with around 10 million ha only in Africa. Wheat is grown on about 5.5 million ha in North Africa and the other important part of wheat production (2.5 million ha) is located in South Africa, Ethiopia, Sudan and Kenya (CURTIS *et al*., 2002). If about 70% of present world wheat production comes from irrigated or high rainfall regions (REYNOLDS & BRAUN, 2013), irrigated wheat is not widespread in Africa (except Egypt where nearly all wheat is irrigated).

According to the UNITED NATIONS (2017), the African continent might host 25 % of global population in 2050 (compared with 15 % in 2010). In these conditions, the risk of widening the already present (endemic) gap between production and consumption of some crops (*e.g*. wheat which is imported in all Africa) is high (MUELLER *et al*., 2012). Due to the increasing demand and huge deficit, wheat distribution is now extending to hotter and drier areas (*e.g*., Nigeria, southern Algeria, southern Libya) (EL SOLH, 2012). Sudan plans to extend wheat production in the high terrace areas in the north, both Eritrea and Ethiopia plan to expand irrigated wheat in mid-altitude and lowlands while other countries (*e.g*. Mauritania, Niger, *etc*.) project to introduce wheat. Enhance crop productivity is however impeded both by the difficulty of adapting current African agronomic practices (intensification, irrigation, mechanization, *etc*.) and by climatic and edaphic conditions worsened by climate change (WHEELER & VON BRAUN, 2013; SERDECZNY *et al*., 2016).

If global circulation models agree on climate warming (with a magnitude dependent on CO_2 concentration scenario), projections for precipitation are much more uncertain for Africa (NIANG *et al*., 2014). Already today, the lack of a consistent coverage of hydrological data (precipitation, soil water content, *etc*.), especially in those regions, makes a good knowledge of the current conditions difficult and, thus, prevents any planning for the future. In such a case, ecosystem models, which spatially and dynamically represent the biogeochemical land surface processes of vegetation and soils, are interesting tools to represent the soil water balance and provide a regional overview of the current and future hydrological conditions. We use here the CARAIB dynamic vegetation model (DURY *et al*., 2011) to evaluate current and future soil water availability resulting from historical climate and its forthcoming variations in African regions above the equator simulated by an ensemble of General Circulation Models (GCMs) and Representation Concentration Pathways (RCPs). Potential impacts of increased temperature and soil water deficit on wheat yields are analysed. Results are discussed taking uncertainties linked to increasing CO_2 concentration and irrigation potential into account.

MATERIAL AND METHODS

CARAIB model

The CARAIB (CARbon Assimilation In the Biosphere) dynamic vegetation model (WARNANT *et al*., 1994; GÉRARD *et al*., 1999; DURY *et al*., 2011) is a process-based model which calculates carbon and water fluxes between the atmosphere and the terrestrial biosphere. It simulates the major processes of the plant development (establishment, growth, decease) as well as their geographic distributions (plant functional types or species) in response to climate change. Its various modules describe respectively (i) soil hydrology, (ii) photosynthesis/stomatal regulation, (iii) carbon allocation and plant growth, (iv) litter/soil carbon dynamics, (v) vegetation cover dynamics, (vi) seed dispersal, and (vii) fire disturbance. Originally dedicated to natural plant types, CARAIB includes now the representation of agricultural plants, crops and meadows (FONTAINE *et al*., 2014; MINET *et al*., 2015) and is involved in different model intercomparison projects (Modelling European Agriculture with Climate Change for Food Security, MACSUR, FRONZEK *et al*., 2018; Global Gridded Crop Model Intercomparison, GGCMI, ELLIOTT *et al*., 2015). The present study focuses on wheat in Africa north of the equator. Wheat is mainly planted in temperate areas (northern and southern Africa) and to a more limited extent in tropical areas, generally at high elevation (eastern Africa).

The vegetation model simulates the crop development from sowing to harvest; the different phenological stages requiring a certain (crop specific) heat accumulation to be reached. Heat accumulation is expressed by growing degree days (GDD), the sum of daily temperature in °C above a certain base temperature below which the plant does not grow. A wheat cultivar is attributed to each grid cell as a function of the cell growing season temperature and soil water availability. With a base temperature of 0 °C for the GDD calculation, wheat germinates when GDD0 = 140 °C days and if soil water conditions are suitable for seed germination. Wheat reaches maturity when GDD0 attain at least 1800 °C days but some cultivars require more (up to 4000 °C days). In the model, stress occurs under critical soil water content (below 15 % of field capacity) and low temperature (below 0° C).

In absence of allocation to harvestable storage organs (*e.g*., cereal grain), crop yield is estimated from net primary productivity using a harvest index (GERBENS-LEENES *et al*., 2009). The model has not been calibrated to reproduce historical yields but the cultivar selection is made to match the observed growing season length. Following the protocol of the GGCMI intercomparison (ELLIOTT *et al*., 2015), we used sowing data from two global crop calendars, MIRCA2000 (PORTMANN *et al*., 2010) and SAGE (SACKS *et al*., 2010). Wheat is sown at the end of the year (October or November) in North Africa and in June in sub-Saharan regions above the equator. These sowing dates are fixed during the simulation period. Wheat is planted every year with no consideration of crop rotation. We prescribed a crop-specific maximum growing season length. If wheat does not reach maturity within 200 days, it is not harvested. A crop mask (white grid cells in yield figures) has been applied to exclude areas that are not croplands (i.e. cool or hot desert) or areas where wheat is not commonly cultivated. The model does not include nutrient limitation nor the effects of pests and diseases.

The soil water balance between water inflows (precipitation and irrigation) and outflows (evapotranspiration, drainage and surface runoff) is simulated for a soil layer corresponding to the rooting zone with a depth depending on vegetation type (*i.e*., 1.25 m for wheat). Soil water (*SW*) is allowed to vary between the wilting point (*WP*) and the saturation. Soil water available for plant growth (*ASW*) is expressed as the fraction between actual soil water and water at field capacity (*FC*): $ASW = (SW\text{-}WP)/(FC\text{-}WP)$. Annual total runoff will be used to evaluate the water amount potentially available for irrigation, assuming that the runoff can be stored for later irrigation needs. In conditions of water deficit, plant growth is reduced due to stomatal closure to prevent water loss. Leaves dry out (and hence leaf area decreases) if evapotranspiration is too large with respect to the amount of water that can be taken from the soil.

Input data

Weather data (daily values of mean air temperature, precipitation, diurnal temperature range, air relative humidity, cloud cover (converted in percentage of sunshine hours) and surface horizontal wind speed), atmospheric CO_2 concentration and soil characteristics are the primary model inputs. For the evaluation of model results on the current period, we use as historical climate the 1980-2010 AgMERRA dataset at a 0.5° spatial resolution (RUANE *et al*., 2015) similarly to GGCMI Model Intercomparison. Future crop projections were performed using the 0.5° 1950-2099 climatic outputs of three General Circulation Models (GFDL-ESM2M, IPSL-CM5A-LR and MIROC5 GCMs), derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5, TAYLOR *et al*., 2012) and previously bias-corrected in the framework of the Inter-Sectoral Impact Model Intercomparison Project Phase 2b (ISIMIP2b, HEMPEL *et al*., 2013; LANGE, 2017). Two different Representative Concentration Pathways are considered: RCP2.6 and RCP6.0 with a radiative forcing of +2.6 (~ 420 ppm) and +6.0 W/m^2 (~ 670 ppm) respectively (van VUUREN *et al*., 2011). Climate and terrestrial ecosystem change are presented by anomalies between the historical period (1970-1999) and the end of the century (2070-2099) .

Climate and water scenarios

Three climate projections allow for a first estimate of the uncertainty in temperature and precipitation changes expected for the end of the 21st century. They all project that annual mean temperature will increase by 1 to 2 °C and by 2 to 4 °C respectively under the RCP2.6 and RCP6.0 trajectories. If they agree on a decrease in precipitation in the Maghreb (from -10 % up to -60 % under RCP6.0), the trends are less clear for the Sahel and the more humid sub-Sahelian regions. IPSL-CM5A-LR and MIROC5 simulate wetter conditions in general, from *a status quo* up to +40 % (with higher percentages for the Sahel currently very dry) while GFDL-ESM2M projects drier climate (decreases up to -30 %). Under RCP2.6, precipitation anomalies are similarly spatially distributed than under RCP6.0 but have a lesser magnitude.

The impacts of atmospheric CO_2 concentration and irrigation on wheat yield are also studied. The uncertainty on the future pathway of greenhouse gases concentration is evaluated using both RCP2.6 and RCP6.0 scenarios (see previous section). And the potential stimulating effect of CO_2 on plant physiology (that corresponds to an increased photosynthetic carbon fixation allowing a better stomatal regulation, and consequently an improving growth and lesser water loss by transpiration) is outlined. Two experiments are conducted: one which only considers climatic conditions associated to CO_2 conditions, which means keeping constant the CO_2 concentration at the 2005 level in the photosynthetic and respiratory processes simulated by the vegtation model, and one in which effects of both atmospheric CO_2 concentration and its associated climatic changes are taken into account. For this last experiment, we developed a new method to simulate a CO_2 fertilization effect limited by available nutrients. This method corresponds to a downregulation of the photosynthetic activity based on empirical values of V_{cmax} (maximum carboxylation rate) and J_{max} (maximum rate of electron transport) derived from experiments performed in a CO_2-enriched atmosphere (AINSWORTH & ROGERS, 2007).

Simulations are performed under two water scenarios: a rainfed (no irrigation, precipitation only) and a fully irrigated (water supplied to reach field capacity assuming unlimited water resources). Under the first scenario, soil water deficit and its impacts on crop production are evaluated. The second scenario allows an evaluation of the amount of irrigation water necessary to fulfill crop requirements.

RESULTS

Current yield simulations

Wheat actual yield (figure 1a) and water-limited yield potential (figure 1b) are provided for some regions in the world by the Global Yield Gap Atlas (GYGA, http://www.yieldgap.org/). The comparison of the wheat yield simulated by the model (figure 1c) with the GYGA wheat yields shows reasonably good spatial correlation with a *r* coefficient of 0.70 and 0.73 if we consider respectively GYGA actual and potential water-limited yields (figure 1d). Model results lie between actual and potential values although generally closer to potential yields. CARAIB simulates yields primarily limited by climatic conditions and not by nutrient or management constraints. LOBELL & FIELD (2007) show that growing season temperatures and precipitation explain one-third to half of interannual variations in global average yields; the remaining percents being due to variations in climate statistics other than growing season averages (here the model takes other climate variables than temperature and precipitation into account, see Input data section), changes in economic and other conditions that influence crop management. Including additional factors would certainly improve model projections but considering climate variations only already provides significant assessment on crop yields and changes. In the humid parts of tropical Africa, the model projects yields of more than 4 t ha^{-1} yr^{-1} when observed yields rarely exceed 2 t ha^{-1} yr^{-1} (*e.g.*, in Ethiopia). Gaps between observed and potential yields are generally high in African regions due to an extensive agriculture, choice of an inadequate cultivar variety, degraded soil, no fertilizer application, diseases and insect pests (MUELLER *et al.*, 2002). Over Europe model yields are yet mostly lower than both observed or potential yields. This surely comes because in the simulation only spring wheat is sown in Europe while in Western and Central Europe winter wheat is also cultivated in areas with mild winter. Already sown in autumn, winter wheat has a longer growing season and generally higher yields than spring wheat.

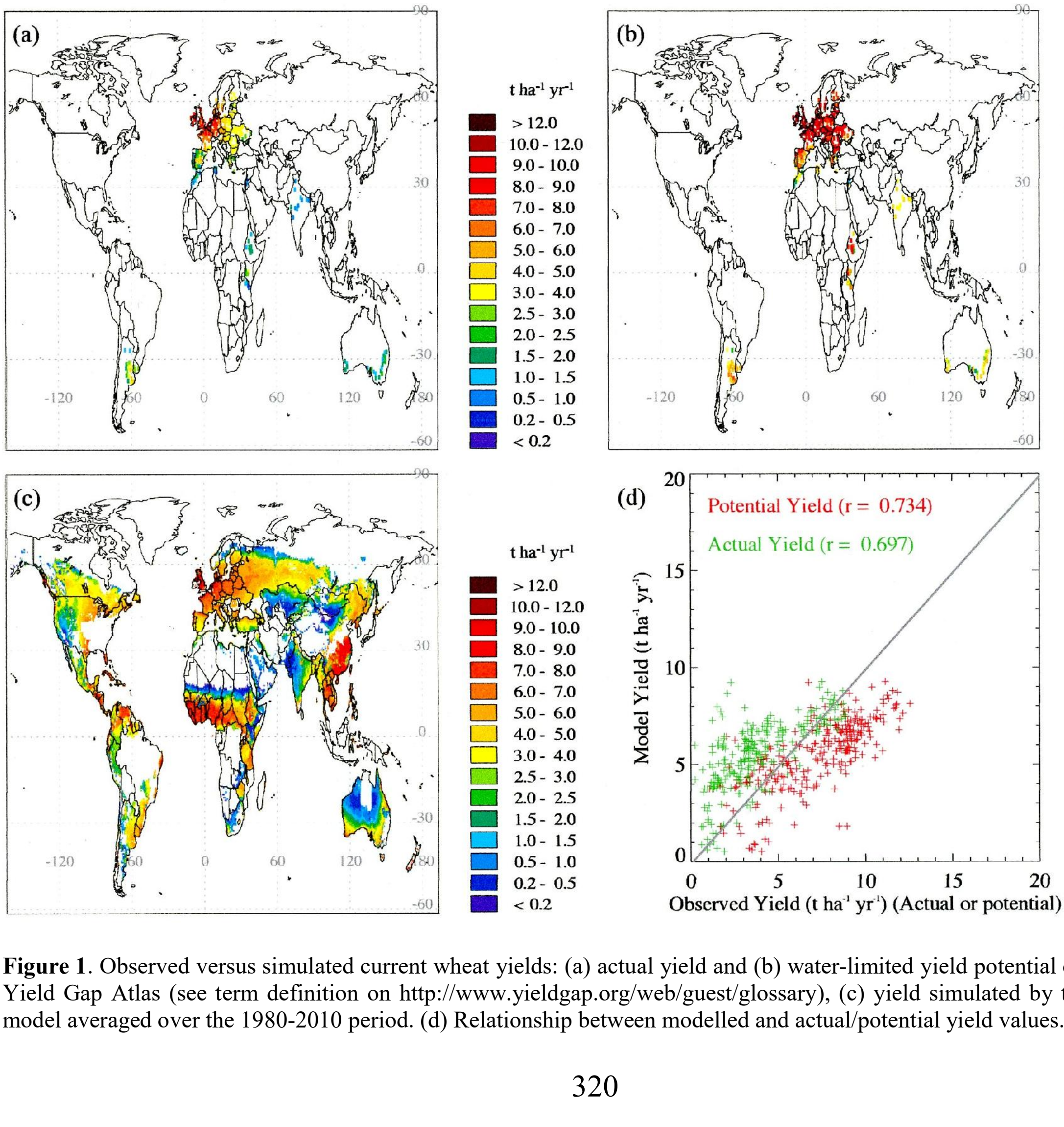

Figure 1. Observed versus simulated current wheat yields: (a) actual yield and (b) water-limited yield potential of the Global Yield Gap Atlas (see term definition on http://www.yieldgap.org/web/guest/glossary), (c) yield simulated by the CARAIB model averaged over the 1980-2010 period. (d) Relationship between modelled and actual/potential yield values.

Irrigation

As already shown by HUBERT *et al*. (1998) and DURY *et al*. (2011) at the global and European scales, the annual water budget simulated by the model is relatively correct since annual runoffs compare rather well with data from the UNESCO atlas (COGLEY, 1998). Over our region of interest, the geographical distribution of runoff is relatively well reproduced (correlation coefficient of 0.85 and a slope of 1.11 between modelled and UNESCO). With a crop-only setup, the model tends to overestimate the annual runoff and thus the water amount potentially available for irrigation, in regions where shrubs and trees are expected to be present. In the absence of irrigation, the soil water available for plant growth simulated by the model (figure 2a) is certainly the primary limiting factor for wheat growth in many African regions (*e.g.*, Maghreb, sub-Sahel, figure 2b). In parallel to this rainfed scenario, we also evaluate how application of irrigation may enhance current wheat productivity. Assuming unlimited water availability, crops are fully irrigated (*i.e.,* at the field capacity level). In these conditions, irrigation is projected to increase yield in areas where soil water content is currently below 50 % of the field capacity (figure 2c). However, in most of these areas, such a level of irrigation is not realistic since the water to apply would even exceed the water amount potentially available from runoff (figure 2d). In fact, there is basically no cultures north of Lake Chad where crop water needs largely go beyond runoff except in the Nile Valley where water can be withdrawn from the river.

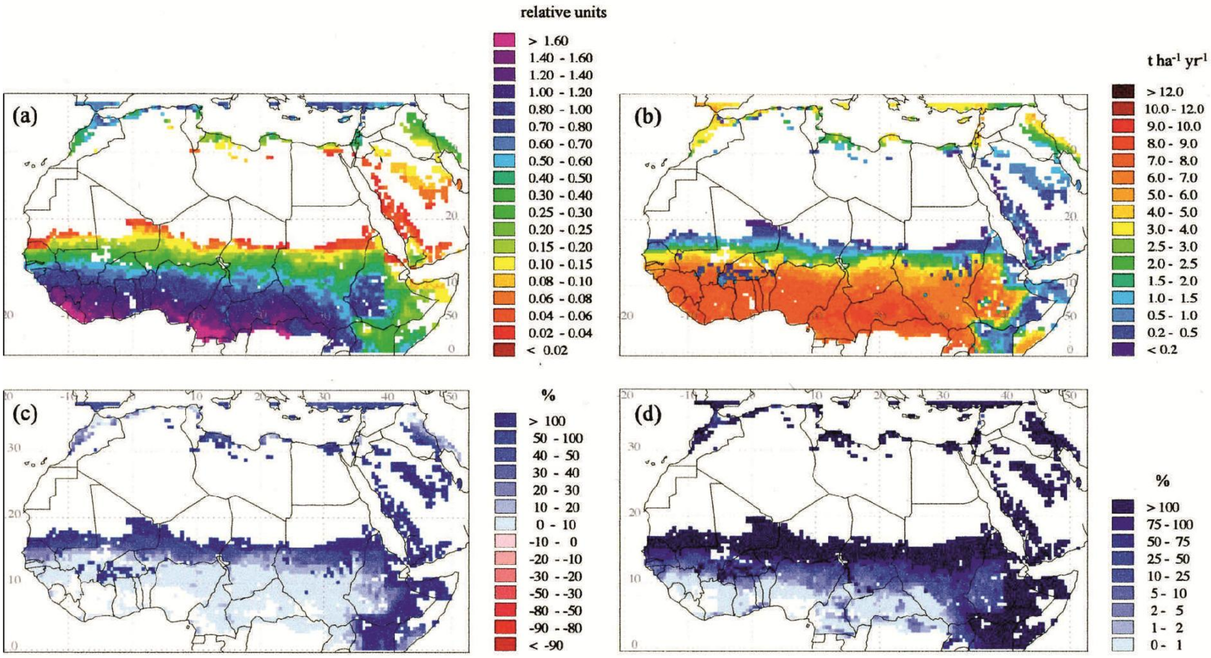

Figure 2. Water availability and wheat yield. (a) Annual mean soil water available for plants (ASW) calculated by CARAIB for the 1970-1999 period. It corresponds to the ratio (W-WP)/(FC-WC) where W, WP and FC are respectively the actual soil water content, the wilting point and the field capacity, and is expressed in relative units. (b) Wheat yield simulated by the CARAIB model averaged over the 1970-1999 period. (c) Potential increase of 1970-1999 yields by irrigation (anomalies between irrigated and rainfed scenarios). (d) Annual amount of applied water to keep field capacity level expressed as a fraction of runoff calculated only with crops.

Future soil water and yield projections

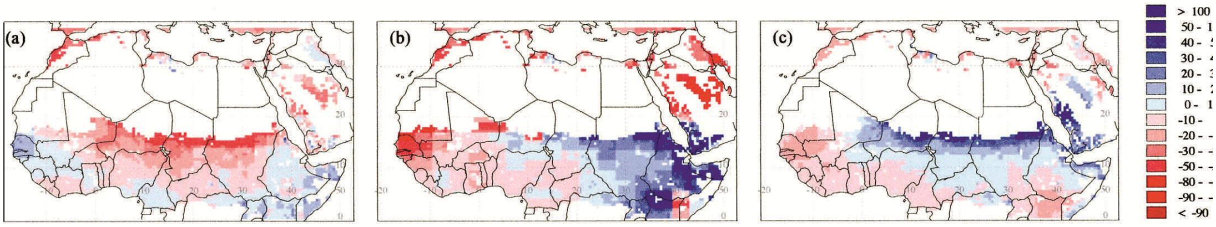

Figure 3. Increasing factor of the annual mean soil water available for plants (ASW) calculated by CARAIB (red and blue indicate respectively decrease and increase) between 2070-2099 period and the 1970-1999 reference period under the RCP6.0 (a) GFDL-ESM2M, (b) IPSL-CM5A-LR and (c) MIROC5 climate scenarios.

Under all three RCP6.0 climate scenarios, CARAIB simulates decrease in soil moisture where precipitation are projected to diminish for the end of the century (figure 3). Temperature rise leading to a higher evapotranspiration enlarges water deficit even in areas of positive anomalies in precipitation. The model projects reductions up to 50 % in Maghreb (with IPSL-CM5A-LR) and in sub-Sahel (with GFDL-ESM2M) for 2070-2099 period. The less pronounced RCP2.6 temperature increase leads to less important changes in soil moisture. The impact on wheat growth and yield will strongly depend on the plant response to increasing atmospheric CO_2 concentration (figure 4). When the potential CO_2 effects are removed (figures 4a,b,c), important decreases in wheat yield are simulated: up to 20 % in humid tropical area and, larger (up to 50 %) in Sahelian and Maghreb regions. One cause is the soil water shortage due to the combination of drier and warmer conditions, as discussed above. A second is the shorter growing season because of climate warming. Mainly controlled by temperature, the time between phenological crop stages is shorter and, maturity and harvest arrive thus earlier. This affects yields by reduced biomass accumulation, especially wheat grain filling. Once the effects of rising atmospheric CO_2 concentration to RCP6.0 concentrations are combined to climate change projected with the same RCP scenario (figures 4d,e,f), CARAIB results indicate a potential stimulation of wheat growth overcoming negative climate change impacts with yield gains around 20 % in sub-Saharan regions (up to 40 % in Eastern Africa).

Despite the effect of carbon dioxide, some negative anomalies in yields are still projected in some Sahel areas (where the simulated historical yields generally do not exceed 1 t ha^{-1} yr^{-1} meaning that crop is probably not grown today) and in Maghreb where high temperature and low precipitation changes are simulated together. Under RCP2.6 scenarios, negative and positive yield anomalies are mainly limited to 10 %. Concerning future needs in irrigation, according to the model, the water amount to apply annually (still to maintain the field capacity) might not increase between 1970-1999 and 2070-2099 periods owing to a shorter growing season. But, the daily need in irrigated water might be larger and difficult to satisfy considering climate projections. Indeed, precipitation (and runoff) are projected to decrease in many areas and extreme rainfall events (increased number of days without rainfall or heavy rain), with their negative impacts on crops, are projected to increase (NIANG *et al*., 2014).

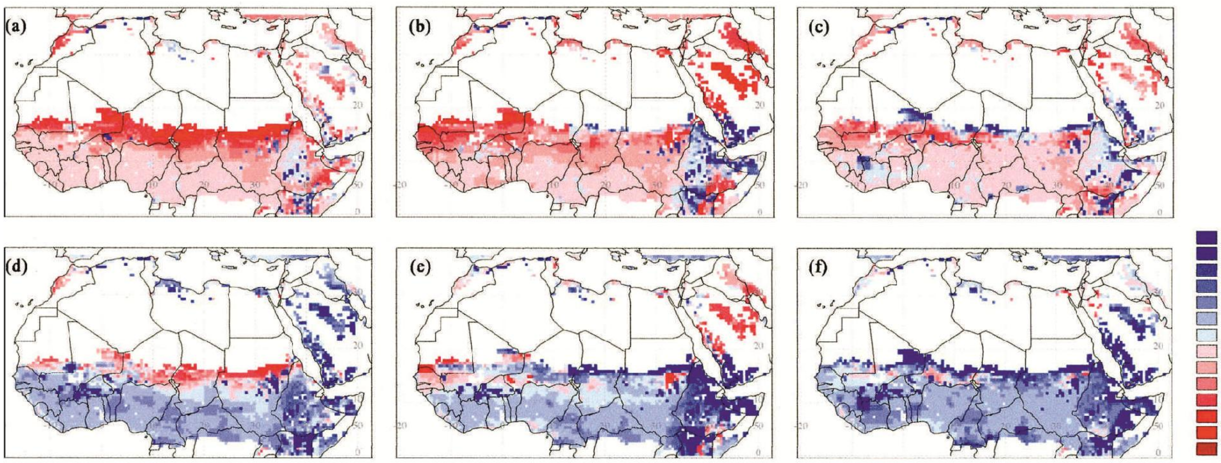

Figure 4. Change in wheat yield projected by the CARAIB model between the end of the century (2070-2099) and the reference period (1970-1999) without ((a) GFDL-ESM2M, (b) IPSL-CM5A-LR and (c) MIROC5 climate scenarios) and with ((d) GFDL-ESM2M, (e) IPSL-CM5A-LR and (f) MIROC5) the CO_2 stimulating effect on plant growth under the RCP6.0 pathway.

DISCUSSION AND CONCLUSION

Numerous recent modelling studies assess the response of crops to climate change at the global scale (ROSENZWEIG *et al*., 2014; DERYNG *et al*., 2016). For example, ZHAO *et al*. (2017) estimate a reduction of wheat yields by 6.0 % for each 1 °C increase in global mean temperature. Researches focusing on African regions are also abundant but wheat is relatively less studied compared to more dominant crops in African agriculture. Sub-Saharan Africa is projected to experience large negative production impacts for many crops (SCHLENKER & LOBELL, 2010). For West Africa, PARKES *et al*. (2018) simulate maize, millet and sorghum response to short term climate change (1.5 °C warmer than the pre-industrial) and project an increase in interannual variability of yield rather than a change in average yields. KNOX *et al*. (2012) show a mean yield change of -17 % for wheat across Africa by the 2050s. In a review of projected impacts of climate change on crop yields in Eastern Africa (ADHIKARI *et al*., 2015), wheat is reported as the most vulnerable crop, for which up to 72% of the current yield is projected to decline by the end of the century.

The present study focuses on wheat and covers sub-Saharan regions above the equator and North Africa at the same time. If direct comparisons with other studies might be difficult primarily due to the various climate scenarios used for driving the models, our results also show the negative impacts of future climate trends (warming and drying) on wheat yields. Depending on the climate scenario, CARAIB simulates important reductions in soil water content in regions where wheat is usually grown (*e.g*., Maghreb) but also in regions where it is newly (or planned to be) introduced (*e.g*., southern Algeria, Mauritania). Results also highlight large uncertainties associated to the parameterization of CO_2 effects. With or without the CO_2 stimulation of plant growth, positive or negative anomalies are respectively projected for the yield of wheat, similarly to other C3 crops. Free-air concentration enrichment (FACE) experiments, that measure the response of plant growth to rising CO_2 concentration, suggest however that model projections might overestimate how increasing CO_2 positively affects yield response to decreased water and increased temperature (AINSWORTH *et al*., 2008). Our scenario which combines a CO_2 stimulation and a downregulation of photosynthesis was applied to better match FACE experiments but long-term plant response to carbon dioxide with a progressive acclimation to increasing CO_2 remain anyway unclear. The uncertainties of carbon dioxide effects are moreover greater in arid and tropical regions because experiments have been carried out mostly in temperate regions of the northern hemisphere. The absence of a nutrient scheme in the model needs also to be taken into account in qualifying wheat yield response to increasing CO_2 and climate change. ROSENZWEIG *et al*. (2014) show that models that include explicit nitrogen stress project more severe impacts. In sub-Saharan Africa, many croplands are highly nutrient-deficient and 67 % are affected by soil erosion (LINIGER *et al*., 2011).

Besides the lack of nutrient limitations, the model does not take, among other things, high temperature mortality, flooding stress, critial stages like anthesis or grain filling whose integration might strengthen model projections. With climate warming, crops might be exposed to critically high temperatures, especially in low-latitude regions where climate is already quite close to plant tolerance to extreme temperature (ASSENG *et al*., 2011). Wheat is generally considered to enjoy an optimum temperature range of 17–23°C over the course of an entire growing season, with a minimum temperature of 0°C and a maximum temperature of 37°C, beyond which growth stops (lethal high temperature of ≈ 47.5°C; PORTER & GAWITH, 1999). If we focus in this study on mean yield change, change in inter-annual variability of yield is just as alarming for food security (AHMED *et al*., 2015).

To test the potential gain in wheat productivity from irrigation, we ran the model under a simplistic scenario assuming unlimited water availability (to keep soil water at field capacity permanently). We compared this additional irrigation water to the grid cell runoff simulated by the model to evaluate the gap between this scenario and actual available water resources. Naturally, this is only a rough estimation; grid cell runoff actually available for irrigation being surely less important (lateral losses, difficulty to implement a large-scale collection of runoff, *etc*.). JÄGERMEYR *et al*. (2016) investigate the potential to increase global crop production through improved crop water management (improving irrigation systems and use of *in situ* precipitation water). Under an ambitious integrated water management scenario, they show that current global production might be increased by 41 % and that potential climate change impacts might be buffered (even if some regions like West Africa remain with negative impacts). However, only 5 % of the cropland is irrigated in sub-Saharan Africa (XIE *et al*., 2014) while CARAIB projects an increase in daily irrigation needs for the end of the century. The future agronomic adaptation of African agriculture is an important source of uncertainties on how negtative climate change impacts will be countered in the future. We show the potential impacts of irrigation but other adaptation measures like change in planting dates or adoption of cultivars more resistant to heat or drought can be taken by farmers. In conclusion, the CARAIB spatial projections of current and future soil water balance and wheat yields, in North and sub-Saharan Africa (above the equator), allow to estimate the potential climate change impacts and highlight the important uncertainties related to increasing CO_2 concentration and irrigation potential. This kind of study can help in the identification of agricultural areas currently vulnerable or which might be exposed in the future. It can also be useful to optimise water resource management in African countries.

ACKNOWLEDGEMENTS

We acknowledge the Inter-Sectoral Impact Model Intercomparison Project Phase 2b (ISIMIP2b) funded by the German Federal Ministry of Education and Research (BMBF, grant no. 01LS1201A1) for producing and making available the bias-corrected outputs of global circulation models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). We also thank the Global Gridded Crop Model Intercomparison (GGCMI) of the Agricultural Model Intercomparison and Improvement Project (AgMIP) for making available historical climate and crop databases.
We acknowledge the MASC project of the Belgian Science Policy Office which allows the crop module refinement of the CARAIB model [BELSPO BRAIN-be program, contract number BR/121/A2/MASC]. The first author is funded by the BELSPO AFRIFORD multi-disciplinary project (BRAIN-be Research Program BR/132/A1/AFRIFORD). Ingrid Jacquemin is funded by the BELSPO MASC project (BRAIN-be Research Program BR/121/A2/MASC). Alexandra-Jane Henrot is funded by the F.R.S.-FNRS under research grant FRS-FNRS X.3041.17—VULPES-Ulg.

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