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ABSTRACT

Bioenergy crops are expected to play an important role in reducing greenhouse gas (GHG) emissions and in enhancing the security of energy supply. According to Sir David King, climate change is our most serious threat. This paper presents some new evidence on the way in which changes to the climate will affect winter wheat yield in Norfolk, England, and there are some surprising but vitally important outcomes. Winter wheat shows different dependence on climate parameters when the temperature is increased, rainfall increased or decreased, and carbon dioxide (CO_2) levels increased. Model predictions showed that under many future climate scenarios winter wheat yield would increase with decrease in precipitation and in temperature ranging from +1.2°C to +3°C. However, increased temperature of up to +6°C resulted in yield decrease under both ambient and elevated levels of CO_2.The combination of elevated temperature and CO_2 slightly increases the yield of the crop.

Keywords: Bioenergy Crops, Climate Change, Winter Wheat, Yield.

1. INTRODUCTION

By the end of the 21st century the world will need to increase energy supply in order to satisfy a projected 15 billion people [1, 2], in the face of growing energy demand, depletion of conventional fossil fuels reserve, and the impacts of climate change. There is clear scientific consensus that climate change is caused by anthropogenic emissions of greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), arising from conventional fossil fuels burning such as coal, crude oil and natural gas [3]. The replacement of these conventional fossil fuels with new renewable, carbon-neutral sources of energy and transportation fuels has become a key objective for policy makers all over the world. There is broad agreement that renewable biomass can be a promising alternative to conventional fossil fuels for producing heat, grid electricity, and transportation fuels [4, 5].

Although, currently only about 14 million ha (1-2% of the world's arable land) is devoted to dedicated bioenergy crops production, this is expected to increase to 4% by 2030 and 20% by 2050 [6] . However, the potential for dedicated energy crops for biofuels production could only be met if high crop yields can be sustained [7] which, depends largely on land availability and, most importantly climate change – since crop production is inherently sensitive to climate and its variability [8-10].

Climate change, which has been projected to continue throughout the 21st century has been shown to have significant impact in terms of greater incidence and magnitude of flood, drought, and hurricanes [11-13], causing tremendous effects on agriculture, natural ecosystem, and the society in general [14, 15] . Over the 20th century, global surface air temperature has already increased by 0.8 °C and is projected to increase by 1.4 – 5.8 °C during the 21st century [16] . Temperature is a major determinant of the rate of plant development [17, 18] and under climate change, increased temperatures that shorten the life cycle of crops have been shown to reduce the yield of crops such as corn [19, 20] and wheat [9, 21]. Thus, changes in precipitation patterns and the frequency of extreme weather events will further complicate impacts on crop yields. These changes will have serious implication on the global production of dedicated bioenergy crops for biofuels causing declines in energy supply due to low feedstock yields [22].

Wheat grains are one of the most common feedstocks used today for bioethanol production. Thus, an assessment on how future climates would influence the productivity of winter wheat would be of great importance to farmers and policy makers.

Given the global concern regarding the vulnerability of bioenergy crops to climate change, there is growing interest, in recent times over the potential link between bioenergy crop production and climate change. For instance, Stromberg *et al.* [23] also investigated the impact of wind damage on biofuel feedstock production, and assessed the effect that a future potential increase in tropical cyclone intensity would have on energy security, rural development and climate change mitigation measures in the Philippines in 2050. Results suggest a modest decrease in biofuel feedstock productivity that is shown to affect the Philippine's policy goals.

Wang *et al.* [24] assessed potential impacts of climate change on wheat production as a biofuel crop in southern Saskatchewan, Canada, using the Decision Support System for Agrotechnology Transfer-Cropping System Model (DSSAT-CSM) to simulate biomass and grain yield under three climate change scenarios (CGCM3 with the forcing scenarios of IPCC SRES A1B, A2 and B1) in the 2050s. Compared with the baseline, precipitation was projected to increase in every month under all three scenarios except in July and August and in June for A2, when it is projected to decrease, while annual mean air temperature was projected to increase by 3.2, 3.6 and 2.7 °C for A1B, A2 and B1, respectively. The model predicted increases in both biomass and grains by 28%, 12% and 16% without the direct effect of CO_2 and 74%, 55% and 41% with combined effects (climate and CO_2) for A1B, A2 and B1, respectively. Similarly, Meng *et al.* [25] evaluated the effects of future environmental changes of CO_2 enrichment and water stress on the growth and biodiesel production of *Jatropha curcas* under two levels of CO_2 concentration (ambient and elevated) and three water regimes (well watered, moderate drought, and severe drought). Elevated CO_2 was found to enhance biomass accumulation of *Jatropha curcas* by 31.5%, 25.9%, and 14.4% under well-watered, moderate drought, and severe drought treatments, respectively.

2. MATERIALS AND METHODS

2.1. Cropping System Model

Carrying out field experiments in order to examine and determine the vulnerability of climate change on winter wheat productivity is practically difficult, time consuming and expensive. However, there are several attempts of utilizing mathematical models that take into account various factors such as; soil characteristics and agricultural practices, plant genotype and physiology as well as climatic data for specified regions. One of the most advanced packages of such models that is currently being used is known as 'Decision Support System for Agricultural Technology-Cropping System Model' (DSSAT- CSM).

2.2. Description of the DSSAT Model

The DSSAT-CSM model [26, 27] was used to investigate the effect of simultaneous changes in T, P, and $[CO_2]$ wheat yield. The DSSAT-CSM is a software application program that comprises crop simulation models for simulating the growth of over 27 crops and is supported by database management programs for soil, weather, and crop management and experimental data and has been validated for over 100 different countries worldwide (see [26]). DSSAT-CSM simulates growth, development and yield of a crop growing on a uniform area of land under prescribed or simulated management as well as the changes in soil water, carbon, and nitrogen that take place under the cropping system over time. DSSAT-CSM is structured using the modular approach described by [28] and [29]. The primary modules for DSSAT-CSM are for weather, soil, plant, the soil-plant-atmosphere interface, and management components. Further details are described in [26].

The DSSAT model comprises the CERES-Wheat (Crop Environment Resource Synthesis-Maize and Wheat) model for simulating the growth and yield of wheat as a function of the soil-plant-atmosphere dynamics, and it has been used for many applications such as regional assessments of the impact of climate variability and climate change and energy crops production [24, 30].

The CERES-Wheat model is a predictive, deterministic model, which stimulate physical, physical, and chemical processes in crop and its associated environment. The model is constructed to simulate primary crop processes as a function of weather, crop management practices, and soil conditions. CERES-Wheat derives daily rates of crop growth (Plant Growth, Regulator, PGR, g plant^{-1} d^{-1}) as the product of light intercepted by the canopy (Incident Photosynthetically Active Radiation, IPAR, MJ plant^{-1} d^{-1}) and radiation use efficiency (RUE, g MJ^{-1}) [30]. The rate of development in CERES-Maize is controlled by temperature (growing degree-days: GDD). Daily crop growth is calculated by converting intercepted photosynthetically active radiation (PAR) into crop dry matter with a crop-specific RUE parameter [26].

The CERES-Wheat model requires a minimum data set for model operation. The dataset encompass data on the site where the model is to be applied, daily weather during the growing cycle, the characteristics of the soil at the start of the growing cycle or crop sequence, and the management of the crop (e.g. seeding rate, fertilizer applications, and irrigation). The model also requires detailed farm level management practices, soil profiles, genetic coefficients describing the crop cultivar, and daily meteorological conditions (precipitation, solar radiation, atmospheric concentration of CO_2, and maximum and minimum temperature). It simulates physiological crop responses on a daily basis as a function of climate factors (daily maximum and minimum temperature, precipitation, and solar radiation), soils, and crop management practices (cultivar, planting date, row spacing, plant population, and planting depth). The model has been applied extensively in many different parts of the world for climate change applications [31-34] . This model computes important biophysical and biochemical processes, like photosynthesis, respiration and transpiration or the dynamics of carbon and water at the leaf-level and are therefore able to simulate the effect of increasing temperatures, changing precipitation and elevated atmospheric CO_2 concentration on crop development and yield [35].

2.3. Climate Data and Climate Change Scenarios

This study adopted the 1981-1990 (10-year) baseline period from the standard 30-year (1961-1990) normal baseline period as defined by the World Meteorological Organisation (WMO), which provides a standard reference for climate change impact studies. Observed 10 year (1981-1990) climate data were obtained for the low-lying area of Norfolk, UK representing daily minimum/maximum air temperature and precipitation. The 10-year observed daily climate data was used as baseline climate scenario.

Climate change scenarios were generated using the observed climate data. Projections were made using the "environmental modification" section of the XBuild module in DSSAT-CSM model, which generate climate change scenarios using various combinations of temperature, precipitation, and atmospheric CO_2 levels. Daily changes in the climate variables were applied to the observed daily climate records. The atmospheric concentration of CO_2 was considered as 330 ppm for the baseline period, which is the default value in the DSSAT-CSM software for the normal baseline reference period (1961-1990) though, in early 2013, atmospheric CO_2 concentrations had increased to about 400 ppm, and is further projected to grow in the future above 660 ppm from the remaining fossil fuel deposits [36]. The factor pull-down menu of the "Environmental modification" section provides 3 options: "Add", "Multiply" and "Replace". For an environmental variable (i.e. minimum and maximum temperature, precipitation, and CO_2), a value was entered in the adjustment box and the type of adjustment was specified using the menu items in the factor pull-down menu.

Observed climate, soil, and crop management practice data from Norfolk, UK was used in the study. Besides data availability, one of the criteria of selecting suitable study sites was their representativeness for the crops. The baseline climate data were modified as follows:

- Daily minimum and maximum temperatures were altered by +1.2, +3.0, +6.0°C
- Precipitation - ±10 and ±20%
- Baseline CO_2 concentration (330 ppm) was altered by +0 (no changes in the CO_2 concentration) and +330 ppm (doubled CO_2 concentration) based on the summary projections by the IPCC AR5 report [37].

2.4. Validation of the Model

To ensure the accuracy of the model predictions, the average simulated grain and biomass yields were compared with yield data from different studies involving the evaluation of climate change impact on crop productivity have been conducted for CERES-Wheat (e.g. [38-43].

3. RESULTS AND DISCUSSIONS

The CERES-Wheat model simulated the average potential grain yield of winter wheat under baseline and future climate change scenarios. The climate change scenarios were applied for the years 1981-1990 (10 years), which represent the baseline condition and run for the combined effect of changing T and P under ambient (330 ppm) and elevated (2X) atmospheric CO_2 concentration $[CO_2]$. In Figures 1 and 2 results of the simulated average potential grain yield under climate change scenarios with ambient and 2X $[CO_2]$ along with the average grain yield for the baseline scenario are presented. Simulated wheat grain yield for the baseline scenario was calculated as 4583.5 kg ha^{-1}. The prediction results of the CERES-Wheat showed that wheat grain would increase as well as increase under the influence of changes in future climates (combined changes in T, $[CO_2]$, and P).

Under ambient atmospheric $[CO_2]$, winter wheat grain yield was predicted to increase by up to 13.1% compared with the baseline scenario when T= +3°C and P= -20% as shown in Figure 1. This could be attributed to the fact that winter wheat grains at surface air temperature of +3°C could be influenced by decrease in precipitation under ambient $[CO_2]$. Similarly, under P=-20% and T=+1.2°C the yield was predicted to increased by about 9% kg ha^{-1} compared with the baseline.

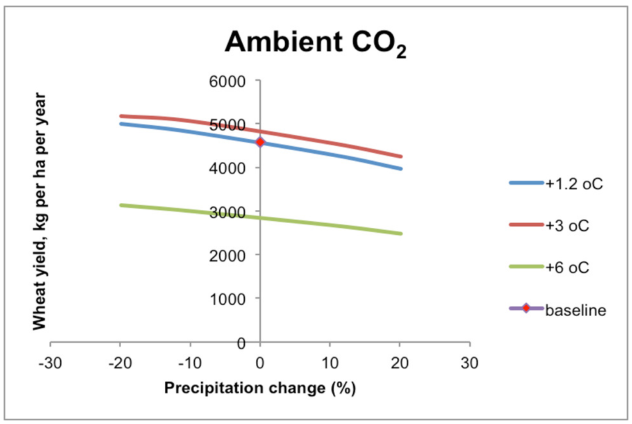

Fig. 1. Influence of combined simultaneous in temperature and precipitation on winter wheat yield under ambient (330 ppm) atmospheric CO_2 concentration

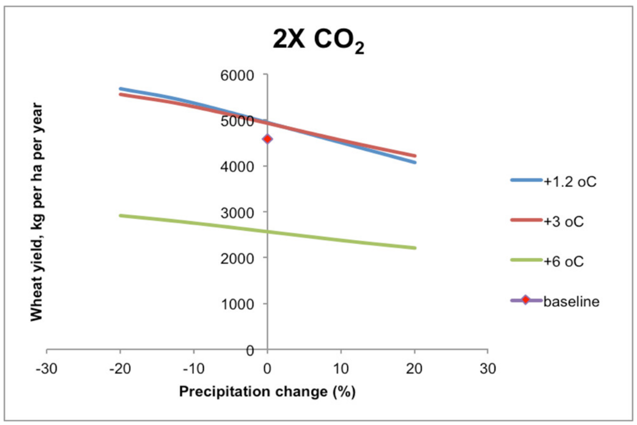

Fig. 2. Influence of combined simultaneous in temperature and precipitation on winter wheat yield under 2X [CO_2] (660 ppm)

In contrast, compared with the baseline scenario, model prediction results under increased *P* amount (+10 and +20%) coupled with increased *T* (+1.2, +3 and +6°C) showed that winter wheat yield would decrease in some climate change scenarios due to the influence of combined changes in *T*, *P*. For instance, at (*P*=+20 and *T*=+6°C), (*P*=+20% and *T*=+1.2°C) and (*P*=+20% and *T*=+3°C) under ambient *[CO_2]* scenario, the yield was predicted to decrease by -45%, -13%, and -7% respectively. This means that the predicted climate changes will have both negative and positive impact on winter wheat yield [38-43].

Moreover, for 2X *[CO_2]*, increased *T* coupled with decreased *P* and increased *[CO_2]* was predicted to have positive impact on potential winter wheat yield under *T*= +1.2 and +3°C scenarios. For instance, compared with the baseline, a yield increase of 24% was predicted by the model at (*T* = +3 °C and *P* = -20%). Moreover, the potential yield was predicted to decrease by -10% at (*T*= 1.2°C and *P*= +20%). This means that winter wheat responds positively to reducing precipitation amounts and also negatively to increasing precipitation amounts with increasing temperature and atmospheric CO_2 levels. It was however, observed that increased precipitation amounts had negative impact on the yield of winter wheat. For example, at (*T*= +6°C and *P*= +20%) under 2X *[CO_2]* scenario, model prediction showed that the yield would decrease by -51.6% compared with the baseline scenario. Similarly, a yield decrease of -10% and -7.6% was predicted at (*T*= 1.2°C and *P*= +20%) and (*T*= +3°C and *P*= +20%) respectively.

Furthermore, result indicates that there is effect of temperature on crop yield presumably due to temperature limitations of photosynthesis [44]. This is because elevated temperatures causes lower photosynthetic carbon assimilation by the crops during their growth and leads, in turn to lower yields. Crop biomass is generally formed through photosynthesis, in which crops utilize atmospheric CO_2 and sunlight to produce high-energy carbonaceous compounds (biomass) [45] . Temperature is a major determinant of the rate of plant development and, which under warmer climate; warmer temperatures have been shown to reduce the yield of a variety of crops such as corn and soybean [45]. However, elevated atmospheric CO_2 concentration tends to reduce the negative effects of rising temperatures

Combined effect of elevated levels of atmospheric CO_2 and surface air temperatures increased winter wheat yield. This is because increasing CO_2 concentration stimulates both net photosynthetic carbon assimilation and biomass production of wheat, a C3 crop, in which at warmer temperatures the net CO_2 induced photosynthetic carbon assimilation, is projected to increase [46].

These results are in agreement with that of [46], which showed that at elevated CO_2 level, net photosynthesis of plants increases by 42% compared to lower CO_2 levels. Net photosynthesis increases with increasing temperature relative to atmospheric CO_2 concentration until optimum growth temperature is reached [47]. But regardless of CO_2 level photosynthesis gradually decrease at temperatures higher than the optimum temperature since increase in temperature reduces photosynthetic efficiency and stimulates photorespiration. Thus, as the climate gets warmer (T= +6°C) the yield of winter wheat according to model prediction would decline in all climate change scenarios considered.

4. CONCLUSION

This research investigated the impact of climate change on winter wheat yield in Norfolk, England using CERES-Wheat of the DSSAT-CSM model. Findings revealed that winter wheat productivity in the low-lying region of Norfolk would be vulnerable to changes in future climates. Moreover, elevated CO_2 is also a strong factor influencing the yield of winter wheat. It is however noted that increased.

Our result suggest that while climate measures are being put in place for climate change mitigation through the use of biofuels in the transport sector, climate change would clearly affect these mitigations measures. However, the impact of climate change on crops would largely depend on the combined effect of projected changes in temperatures, precipitation and elevated atmospheric CO_2 concentration.

More research is therefore required under field conditions to better understand feedbacks between changes in precipitation, temperature, and the magnitude of the CO_2 fertilization effect on bioenergy crops yield. Better understanding of underlying mechanisms of potential changes in crop tolerance to stress under elevated CO_2 is particularly important.

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