Simulation of Crop Productivity for Evaluating Climate Change Effects

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1. Introduction

The effect of climate change on the crop productivity is usually investigated with the experimental methods using a growth chamber or with the numerical methods using a crop model.

The objectives of this research are (1) to establish the crop parameters in a crop growth model for wheat and maize as main crops in the world based on the experimental data collected in Adana and (2) to evaluate the effects of elevated CO_2 concentration and risen air temperature on crop growth.

2. Materials and methods

The SWAP model which was developed in the Netherlands (van Dam *et al*., 1997) was used for the study. The model aims at simulating water, solute and heat transport in relation to plant growth at field scale level and for entire growing seasons. The SWAP model integrates soil-water balance and crop growth originally developed as the WOFOST model to describe daily phenological development and growth in response to environmental factors such as soils and climate, and crop management (Boogaard *et al.*, 1998). The model is eco-physiological process-based, simulating photosynthesis, evapotranspiration, and other major plant and soil processes. The major processes for crop growth are phenological development, CO_2-assimilation, respiration, partitioning of assimilates to the various organs, and dry matter formation.

The SWAP requires input data on soil, crop and climate for its calibration and validation in the different environments. Climate (solar radiation, maximum and minimum temperatures, relative humidity, wind speed and rainfall), soil (soil water retention and hydraulic functions) and crop management data (crop calendar, some growth parameters, irrigation etc.) were collected for the study location. The main parameters of the crop growth sub-model are temperature sum for the development rate of crop, specific leaf area, life span of leaves at optimum conditions, initial total crop dry weight, conversion of assimilates into biomass, fraction of dry matter increase partitioned to organs, maintenance respiration, reduction factor for senescence. Parameters for the crop growth model was decided with the crop growth measurement of two growing years for wheat and one growing year for maize.

The processes and relations incorporated in the WOFOST model are as follows: Using the absorbed radiation, which is absorbed by the canopy and is a function of incoming radiation and crop leaf area, and taking into account photosynthetic leaf characteristics the potential gross photosynthesis is calculated. The potential photosynthesis is reduced due to water and/or salinity stress, as quantified by the relative transpiration, and yields the actual gross photosynthesis. Part of the carbohydrates (CH_2O) produced are used to provide energy for the maintenance of the existing live biomass (maintenance respiration). The remaining carbohydrates are converted into structural matter. In this conversion, some of the weight is lost as growth respiration. The dry matter produced is partitioned among roots, leaves, stems and storage organs, using partitioning factors that are a function of the phonological development stage of the crop. The fraction partitioned to the leaves, determines leaf area development and hence the dynamics of light interception. The dry weights of the plant organs are obtained by integrating their growth rates over time. During the development of the crop, part of living biomass dies due to senescence. Some simulated crop growth processes are influenced by temperature, like for example the maximum rate of photosynthesis and the maintenance respiration. Other processes, like the partitioning of assimilates or decay of crop tissue, are steered by the phenological development stage (van Dam *et al.*, 1997).

The impacts of elevated CO_2 concentration and risen air temperature on crop growth and water balance components for wheat and second crop maize were examined using meteorological data of the Turkish Meteorological Station.

3. Results and discussions

Calculated and measured leaf area index (LAI) and biomass are compared in Fig. 1 for wheat in 2004/2005 and Fig. 2 for maize in 2004, respectively. The biomass values shown in these figures are total above-ground biomass. Although the discrepancy between calculated and measured values is recognized, estimation of crop growth with the SWAP model is satisfactory. The most sensitive parameters for crop growth simulation were found to be temperature sum for the development rate of crop, specific leaf area (i.e. the increase of the leaf area of the crop per kg weight increase of the living leaves) and initial crop total dry weight.

Since CO_2 is the fundamental parameter for crop growth prediction, it is supposed that use of only climatic data would cause the erroneous results. Thus, effects of elevated CO_2 concentration on plants should be imposed to the model simulations. Maize is one of C4 plants, and increases of CO_2 concentration are not so effective in crop growth unlike C3 plants. Although wheat is a C3 plant and elevated CO_2 concentration promotes photosynthesis, risen temperature may partially compensate it with stomatal closure. In fact, elevated atmospheric CO_2 concentration increases photosynthesis in C3 plants and reduces evapotranspiration in both C3 and C4 plants due to reduced stomatal conductance.

Since CO_2 concentration is supposed to increase up to doubling concentration under SRES A2 scenario (IPCC 2001) in 2070s, simulation was done using 2004/2005 meteorological data under doubling CO_2 concentration condition. In doing calculation, the percent change in acclimatized photosynthesis rate was assumed to be +27% and +4% for wheat and maize, respectively (Cure and Acock, 1986). As the result, it was found that biomass values under the doubling CO_2 condition are about 17% and 5% higher than the values under the current CO_2 condition both for wheat and maize, respectively.

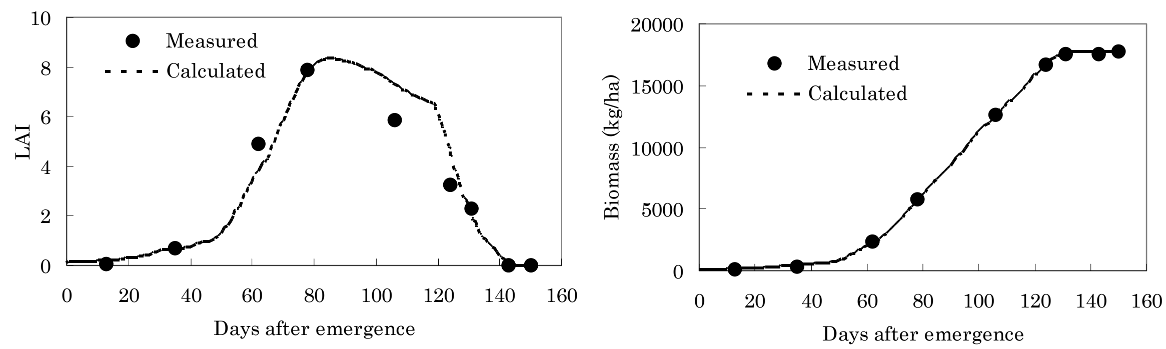

Fig. 1. Comparison between calculated LAI and biomass, and the measured ones of wheat.

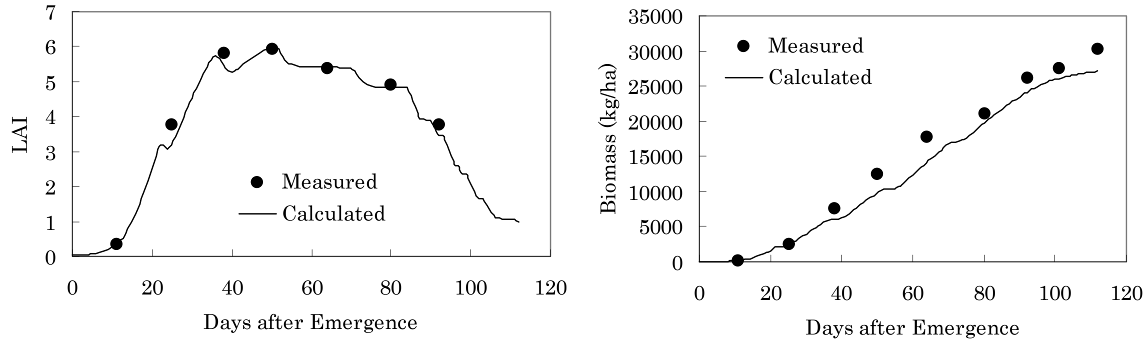

Fig. 2. Comparison between calculated LAI and biomass, and the measured ones of maize.

However, high temperatures accelerate the phenology of plants, resulting in quicker maturation. The shortened growth cycle, in turn, may reduce the yield potential of annual crops (Rosenzweig and Hillel 1998). Based on a range of several current climate models, the mean annual global surface temperature is projected to increase by 1.4 to 5.8 ℃ over the period of 1990 to 2100 (IPCC, 2001). In order to evaluate the positive effect of elevated CO_2 concentration and the negative effect of risen air temperature on crop yields, simulation was done by doubling CO_2 concentration and by increasing maximum and minimum temperature by 1, 3, 5 ℃ relative to the current condition.

Results of calculated yields as well as evapotranspiration (ET) are shown in Table 1 and Table 2 for wheat and maize, respectively. Increase of biomass due to doubling CO_2 concentration is about 15% and 6% for wheat as a C3 crop and maize as a C4 crop, respectively. On the other hand, ET does not similarly increase and even decreases for maize, probably due to temporal water stress resulted from active crop growth. Decrease of biomass and ET following temperature rise is clearly shown in the both tables which denote that temperature increase of 3 ℃ results in biomass decreases by 17% and 20%, respectively. ET decreases similarly as biomass does.

Thus, increased yields by doubling CO_2 concentration are counteracted by rise in temperature of 3 and 1 ℃, respectively for wheat and maize. More than 1 ℃ of temperature rise is estimated in 2070s when CO_2 concentration is supposed to increase up to doubling concentration, although much variations of temperature rise is recognized among models. Detailed description about temperature projection is given in the article "Prediction of Future Change of Water Demand Following Global Warming in the Cukurova Region, Turkey" by Yano *et al*. of this issue.

Reduction of ET due to stomatal closure is not considered in Table 1 and 2. Experimental findings indicating considerable decreases in actual ET due to stomata closure under elevated CO_2 concentration have received a wide recognition (e.g. Ainsworth and Long, 2005). Decreases in transpiration by 17% and 26%, respectively for wheat and maize have been reported by Cure and Acock (1986). Further decreased ET values are replaced with those in Table 1 and 2 as shown in **Table 3**. Thus, ET from wheat and maize further decreases by 54 and 111 mm by transpiration reduction.

Table 1 Effects of doubling CO_2 concentration ($2xCO_2$) and rise in air temperature (+T) on crop growth and ET for wheat without ET reduction

Factor	Biomass (ton/ha)	Grain yield (ton/ha)	Growth days	ET (mm)
Control	17.74	4.71	164	370.4
$2xCO_2$	21.67	5.74	162	371.4
+1 ℃	16.41	4.14	155	350.3
+3 ℃	13.21	3.96	141	310.4
+5 ℃	10.37	4.01	128	254.3

Table 2 Effects of doubling CO_2 concentration ($2xCO_2$) and rise in air temperature (+T) on crop growth and ET for maize without ET reduction

Factor	Biomass (ton/ha)	Grain yield (ton/ha)	Growth days	ET (mm)
Control	27.14	17.29	120	378.4
$2xCO_2$	28.85	17.98	120	359.0
+1 ℃	25.13	15.83	116	361.7
+3 ℃	21.71	13.14	110	335.2
+5 ℃	18.62	10.79	107	314.4

4. Conclusions

In this research, crop parameters in a detailed crop sub-model of the SWAP model were decided for wheat and maize using the field data of two growing years (2003/2004 and 2004/2005) for wheat and one growing year (2004) for maize in Adana. Consequently, the simulated values for LAI and biomass are in reasonable agreement with the measured data.

Then, the effects of elevated CO_2 concentration and risen air temperature on crop growth and evapotranspiration were separately evaluated using created meteorological data based on the observed data in 2004 and 2005.

Increase of biomass due to doubling CO_2 concentration is about 15% and 6% for wheat as a C3 crop and maize as a C4 crop, respectively. On the other hand, ET does not similarly increase and even decreases for maize. Decrease of biomass and ET following temperature rise is clearly shown that temperature increase of 3 ℃ results in biomass decrease for 17% and 20%, respectively. ET decreases similarly as biomass does.

Increased yields by doubling CO_2 concentration are counteracted by rise in temperature of 3 and 1 ℃, respectively for wheat and maize. More than 1 ℃ of temperature rise is estimated in 2070s when CO_2 concentration is supposed to increase up to doubling concentration, although much variations of temperature rise is recognized among the different models.

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Table 3 Effects of ET reduction on crop growth and ET for wheat and maize at doubling CO_2 concentration ($2xCO_2$)

Crop	Biomass (ton/ha)	Grain yield (ton/ha)	Growth days	ET (mm)
Wheat	22.06	6.15	162	317.8
Maize	28.44	17.74	120	248.2

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