Modeling the impact of climate change on wheat production in the Mediterranean environments- Incorporation of the frost damage on grain setting and parameterization of phenology sub-model -

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1. Introduction

We have been developing a simplified process model for simulating wheat growth under the Mediterranean environments. The outlines of our wheat model are first described, followed by describing how to incorporate the effect of frost damage on grain setting and parameterize phenology sub-model. A warm winter may alleviate the frost damage at the ear formation stage, but also has a possibility to worsen it through making the sensitive stage meet the coldest season in a year as a result of accelerated phonological development. A barley model, which has a similar structure to the wheat model and had already been parameterized, was used to demonstrate its ability to explain and predict such complicated influence of global warming on the frost damage.

2. Structure of a wheat growth model

A simplified process approach was employed in our wheat model to simulate crop growth and yield. The model includes four sub-models related to phenology, LAI growth, biomass production and yield formation.

Crop growth rate (CGR) is simply calculated based on radiation use efficiency (RUE) and intercepted solar radiation. To estimate CGR under drought conditions, we use an empirical relationship between transpiration rate and soil moisture based on an experimental result (Kobata 2004, Kobata et al. unpublished and Fig. 1). These processes are expressed as the following equation:

$$CGR = RUE \cdot S_s \{1 - \exp(-k \cdot LAI)\} \frac{T_a}{T_p} \qquad (1)$$

$$\frac{T_a}{T_p} = f(FTSW) \qquad (2)$$

where S_s, k, LAI, T_a, T_p and FTSW is global solar radiation, light extinction coefficient, leaf area index, actual and potential transpiration rate, and fraction of transpirable soil water content, respectively.

Crop development stage is quantified by a continuous variable termed DVS (DeVelopment Stage) as in de Wit et al. (1970). DVS is defined to be 0, 1, 2 at emergence, heading and maturity, respectively. The value of DVS at any moment is given by integrating the development rate with respect to time:

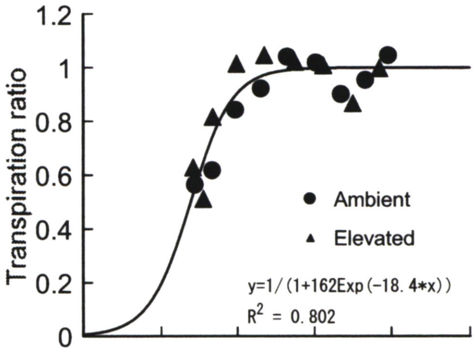

Fig. 1. The ratio of transpiration rate under desiccated soil to under well-irrigated condition for a spring wheat 'Adana99' grown under different CO_2 conditions with pots as a function of the fraction of transpirable soil water content (FTSW) (Kobata et al. unpublished)

$$\mathrm{DVS} = \sum_{i=0}^{t} \mathrm{DVR}_i \qquad (3)$$

where $\mathrm{DVR_i}$ is the development rate at the ith day.

Temperature (T) and daylength (L) responses of DVR in the preanthesis phase can be given by the following equation.

$$\mathrm{DVR} = \frac{1}{G} f(T) g(L) \qquad (4)$$

where G is the minimum number of days required for the completion of one phenophase under optimum T and L, and f(T) and g(L) are the functions giving the temperature and daylength effects on development.

Introduction of the G parameter makes the ranges of f(T) and g(L) 0 to 1, respectively.

For the function f(T), the logistic equation (3) can be successfully applied to the preflowering development process if the supraoptimum temperature range can be omitted from the analysis.

$$f(T)=\frac{1}{1+\exp\{-A(T-Th)\}} \qquad (5)$$

where A and Th are parameters.

The effect of daylength, g(L), can be approximated by the following equation:

$$g(L)=\begin{cases}1-P\exp\{-B(L-Lc)\}, & (L\geq Lc)\\ 1-P, & (L<Lc)\end{cases} \qquad (6)$$

where P, B and Lc are parameters. P is the daylength sensitivity factor ($0\leq P\leq 1$) and Lc means the critical daylength when P = 1.

Those six parameters can be estimated from the phenology data in winter cereal crop species grown under various environmental conditions with iteration methods.

The model is based on the principle that the grain yield (Y_G) forms a specific propotion of the total dry matter production (Wt) of a crop:

$$Y_G=hWt \qquad (7)$$

where h is the harvest index. In the model, h is represented as a function of yield loss rate (γ):

$$h=h_m(1-\gamma) \qquad (8)$$

where h_m is the maximum harvest index and γ is defined as a function of temperature.

3. Wheat experiments for parameterization of the model

Wheat field experiments has been done and are being carried out in Adana, Turkey, to obtain crop data which are required for the development and test of wheat growth models including our model. A Turkish wheat cultivar 'Adana 99' is used for the experiments. Two or three cropping seasons were and will be planned in Adana in 2003/2004 and 2004/2005, respectively. The phenology of 'Adana 99' has been and is continued to be observed also in a series of field experiments with different sowing dates in Ishikawa, Japan. Days to anthesis of Adana99 was strongly influenced by air temperature (Fig. 2). Those phenology data both in Adana and Ishikawa will be used for the estimation of parameters of the model.

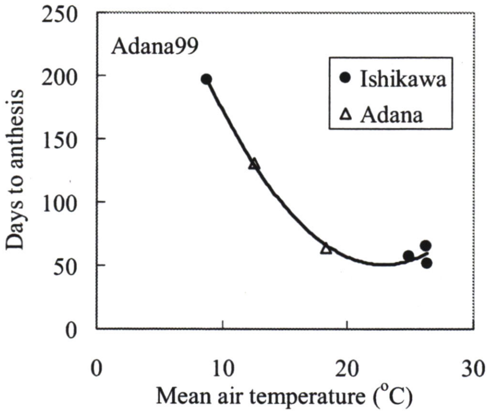

Fig. 2. Days from emergence to anthesis of a spring wheat 'Adana99' grown at Ishikawa in Japan and Adana in Turkey with different sowing dates as a function of mean air temperature until anthesis.

Table 1. Sowing, emergence, anthesis and maturity dates of a Turkish spring wheat 'Adana99' grown at different growth seasons in Ishikawa, Japan, and Adana, Turkey in 2003/2004.

Sowing	Emergence	Anthesis	Maturity
Ishikawa, Japan			
10 Oct, 03	16 Oct, 03	30 Apr, 04	15 Jun, 04
2 Jun, 04	6 Jun, 04	2 Aug, 04	-
16 Jun, 04	20 Jun, 04	11 Aug, 04	-
2 Jul, 04	6 Jul, 04	9 Sep, 04	-
Adana, Turkey			
17 Nov, 03	30 Nov, 03	9 Apr, 04	17 May, 04
4 Mar, 04	15 Mar, 04	18 May, 04	14 Jun, 04

4. Modeling the frost damage

Global warming should accelerate the phenological development of winter cereal crops and then would increase the possibility to make the sensitive stage of them meet the coldest season in a year. Thus, we have to know the effect of low temperature on yield loss rate (γ) at a given phenological stage and also need a precise prediction of phenological stage. For the latter requirement, our phenology sub-model can accurately predict phenology, as demonstrated in the application to a barley cultivar (Fig. 3).

For the former requirement, we can fortunately use published data. Tajima (1982) gave cold temperature treatments to barley at different development stages of young ear. They measured the mortality of young ear under various temperature conditions and showed the sensitivity to freezing temperature increased with the progress of ear development. Dead ears are partly compensated by the growth enhancement of remaining tillers. Therefore, he also gave a relationship between mortality rate of young ear and yield loss rate.

In our model, the phenological stage of young ear is converted into DVS in the phenology model. We made an expression to give a relationship among yield loss rate for barley (γ), daily minimum temperature ($T_{\min}$) and DVS, based on reanalysis of the published data (Tajima, 1982):

$$\gamma = \begin{cases} 0.406(DVS-0.523)(-T_{\min}-2), & (0.523 \le DVS \le 0.8) \\ 0.113(-T_{\min}-2), & (0.8 < DVS < 1.2) \end{cases} \qquad (9)$$

γ equals zero in the case of $T_{\min} > -2$ °C or $DVS < 0.523$. When the DVS is between 0.523 and 1.2, daily values of γ are calculated with equation (9) and finally the maximum value of γ is chosen for the calculation of yield.

We are now searching similar data to make an equation for estimating the frost damage on wheat production.

5. Demonstration of a barely model

We have already developed and parameterized a barley growth model of which structure is very similar to the wheat model. This barley model was used to demonstrate the ability of simplified process models to simulate phenological development and yield.

The phenology model (equation (5) and (6)) was parameterized by using heading dates of a barley cultivar, 'Amagi-Nijo', grown at different growth seasons in Kyoto, Japan. The model and estimated parameters were tested using an independent set of heading dates of Amagi-Nijo grown at 13 different sites in Japan. Fig. 3 shows comparison between observed and estimated days to heading. The close relationship of the figure suggests that our modeling approach can precisely simulate phenological process towards heading under a wide range of temperature and day length conditions.

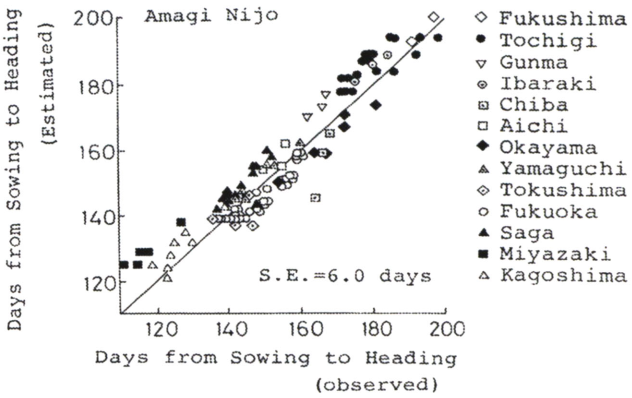

Fig 3. Comparison between estimated and observed days after sowing to heading in a barley cultivar 'Amagi-Nijo' grown at different sites in Japan.

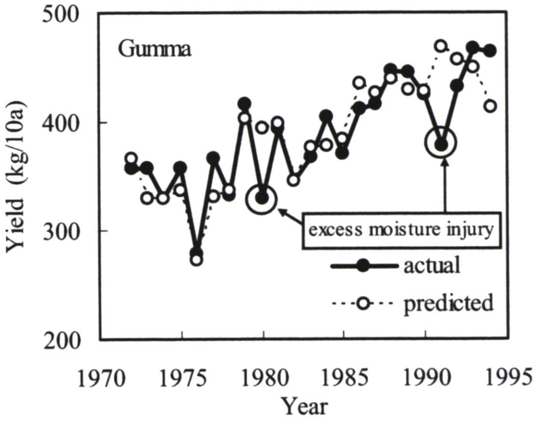

Fig. 4. Actual and simulated beer barley yield in Gumma, Japan.

Fig. 4 shows the historical yield data of a barley cultivar, 'Amagi-Nijo' in Gumma prefecture in Japan with simulated yields. In this case, simulated potential yields were converted into actual yield levels by using a concept of 'technological coefficient (Horie et al., 1995). Excluding the years with excess moisture injury, the barley model well simulated year-to-year variation in barley yield. The effects of planting date on barley yield were also simulated by the model at Tochigi, Japan, under the current and changed climate conditions. The optimum planting date was estimated to be in October under the current climate, which agrees with the actual sowing time in the prefecture. Around Tochigi region, we sometimes experience the severe frost damage on barley and wheat production. A steep yield reduction was simulated in September

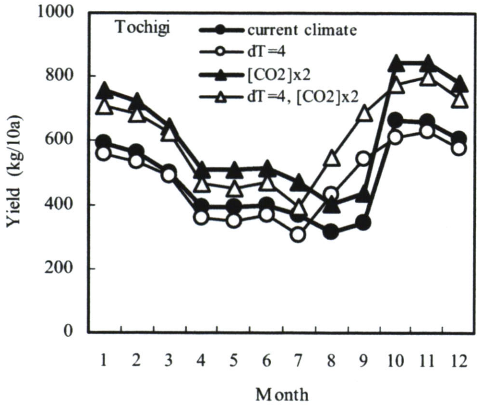

Fig. 5. Simulated relationship between barley yield and sowing date under the current and three changed climate conditions in Tochigi, Japan.

due to the occurrence of the frost damage. Under the elevated temperature conditions, the frost damage was estimated to be alleviated for barley crops sown in September, but to be worsened for those in October in some years due to the acceleration of phenological development. These results suggest our model can deal with the complex nature of the frost damage.

6. Acknowledgements

We are grateful to Prof. Riza Kanber and his staffs for their support to accomplish wheat experiments at Çukurova University in Adana, Turkey.

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