Doctoral Thesis

Modeling and Predicting Wheat Phenological Development Using Meteorological Information

Supervisor Professor Kazuyuki MORIYA

Department of Social Informatics
Graduate School of Informatics
Kyoto University

Satoshi KAWAKITA

September 2020

Modeling and Predicting Wheat Phenological Development Using Meteorological Information

Satoshi KAWAKITA

Abstract

Information about crop phenology, such as heading, flowering, and maturity, can be used to schedule agricultural practices (e.g., fungicide/fertilizer applications or harvesting). Therefore, predicting crop phenology is an important part of efficient agricultural decision making. Furthermore, the duration of crop development can be used to estimate yield or biomass, which means that predicting the phenological development of a crop has a number of useful applications. Crop science studies and bioinformatics have shown that climatic factors strongly influence crop development. Furthermore, recent developments in sensing and information communication technologies have enabled researchers to collect meteorological data and to show the effects of climate on crops, which means that there is a growing opportunity to utilize environmental information to describe crop development. Despite the increase in the applicability of the meteorological data, crop development data are still limited because it takes a long time to collect. Thus, modeling techniques that can predict crop development with limited training data are demanding, and utilizing information processing techniques, such as model algorithms, statistical analyses, and optimization, are expected to improve crop models.

This study explored the application of meteorological and crop development data and how modeling techniques can be used to improve crop phenology prediction. It also provides examples of how meteorological and biological crop development information can be combined with information processing techniques to improve agricultural management. Taking the development of a model for predicting wheat (*Triticum aestivum* L.) phenology as an example, this study showed that improving model structures and selecting optimal parameterization methods for model calibration can improve the accuracy and the certainty surrounding predictions about wheat phenology.

Firstly, I modified the conventional wheat phenology model by adding a vernalization function into the model and evaluated whether it can improve flowering prediction in winter-type cultivars (Chapter 2). This modification was carried out because the existing wheat development models used in Japan were developed for spring-type wheat, which

does not have a vernalization requirement. Therefore, the current models are not very applicable to winter wheat cultivars because they do not consider the vernalization requirement, which means that a new model needs to be developed applicable to winter wheat cultivars. This new, modified model can predict the flowering date of wheat within 1−3 days in terms of the root mean square error (RMSE), which is 0.5−2.5 days smaller than the existing models. Furthermore, I also clarified that a particular bias, which is related to seeding date, was produced for both spring and winter-type cultivars when using the conditional models, and that this new model could improve the bias.

Secondly, I calibrated the wheat phenology models using different parameterization methods and evaluated which parameterization methods could determine the parameters of the models that would avoid prediction and parameter uncertainty (Chapter 3). Three different parameterization methods (the augmented Lagrange multiplier method (ALM), the Nelder-Mead method (NM), and the Bayesian optimization with the Gaussian process (BO)) were used to investigate model accuracy and uncertainty. Previous studies have compared different crop phenology models; however, few studies have paid attention to whether model accuracy and parameter uncertainty varied depending on the differences in parameterization methods. Therefore, I tested the effects of the parameterization differences on prediction accuracy using three winter wheat phenology models with different structures, i.e., the Agricultural Production System Simulator model for wheat (APSIM-wheat), the Wang and Engel model, and the sigmoid and exponential function based (SEB) model, which are proposed in Chapter 2, as case studies. The results showed that parameter uncertainty and precision of prediction were especially affected by the parameterization methods used in the SEB model. The uncertainty parameter increased when using the NM and BO methods. Furthermore, the precision of predication declined when the BO method was used to calibrate the SEB model, which suggested that the ALM method was the most appropriate among the three parameterization methods. The APSIM model showed relatively stable prediction accuracy and parameters regardless of the parameterization method used, which indicated that these factors could vary depending on which models are used. Although modelers can show the variety of crop environmental responses by increasing the number of parameters in the models, it has been found that this process can increase the risk of overfitting. Therefore, it is essential to carefully select the parameterization methods when applying a model with many parameters.

Finally, as an example of a wheat development model application, I used the SEB wheat development model to investigate how wheat phenology can be changed by rising temperature and discuss its influence on Japanese wheat cultivation (Chapter 4). Temperature is one of the most influential factors affecting crop phenology. The IPCC forecast in 2014 suggests that it is highly probable that we will experience more frequent hot and fewer cold temperatures in most areas on seasonal and daily timescales as global mean surface temperatures increase.

In this study, two spring-type wheat cultivars and three winter-type wheat cultivars were assumed to be grown at two locations in Japan during six different sowing seasons from October to December to investigate how the heading date of wheat can change under nine different warming scenarios. The results showed that if the mean temperature rise was 5 ℃ above the average temperature between 1981 and 2010, then the growth of spring-type cultivars, in particular, increased rapidly, and the shortening period for heading varied widely depending on the timing of the seeding date (around 30−80 days). As I found that the advancement of heading date of spring-type cultivars got small as the sowing date became late, delaying sowing time was suggested to be effective for spring wheat cultivation under rising temperatures. Meanwhile, the timing of seeding did not influence on the advancement of heading in winter wheat as much as with spring wheat, and the range was about 20−35 days. However, the period varied depending on the growing conditions because the wheat grew faster in cooler places (about 20−30 days) than in warmer places (about 30−35 days). In Japan, early-maturing cultivars have been developed that can be harvested before the start of the rainy season. However, as the phenology advances due to warming, it has been suggested that there may be more opportunities to cultivate late-maturing cultivars, which have a higher yield capability than early-maturing cultivars.

The results of the studies mentioned above have led to two suggestions about the wheat phenology model calibration. The first is that a vernalization function needs to be added to the models for spring and winter-type wheat development. The second is to pay careful attention to the choice of parameterization methods, especially when using models with more parameters. Furthermore, the results suggest that ALM is the best method for determining model parameters because it avoids parameter and prediction uncertainty. As an adaptation to warming, it has been suggested that delaying sowing may be particularly effective for spring-type wheat cultivation. Also, it was suggested that changing winter wheat, which has vernalization requirements, from spring-type wheat can ease the earliness of heading and reduce the risk of frost damage. The advancement of phenology does not always negatively impact wheat cultivation in Japan, and it has been suggested that changing agricultural practices and using new cultivars can mitigate the impact of climate change. The advances in sensing and information processing technologies have increased opportunities to use meteorological information to describe or predict crop development, and the methodology and knowledge verified in this study can also be applied to other crop models.

Chapter 1

Background

Summary

The primal objective of the present research is improving the prediction and uncertainty of the wheat development model and understanding how wheat phenology can be changed with rising temperatures by utilizing the wheat phenology model. Through this study, I explored the applicability of meteorological information and information processing techniques (e.g., modeling techniques and statistical analysis) for obtaining/estimating important information in agriculture.

Although wheat has different phenological development stages until maturing, I especially focused on predicting heading date or flowering date (after 1-2 weeks after heading) from seeding date because not only these dates are especially important information for farmers to know the timing of spraying fungicide but also because the predicting them is especially complicated since several factors such as temperature, photoperiod, and vernalization involve during the period. Firstly, I modified the existing model developed for mainly spring-type wheat in Japan for adapting to winter-type wheat by adding a vernalization function into the model and evaluated to what extent it improved the flowering prediction for winter-type cultivars (Chapter 2). Secondly, I calibrated the wheat phenology models using different parameterization methods and evaluated which parameterization methods were useful for determining the parameters of the models for avoiding prediction and parameter uncertainties (Chapter 3). Next, based on the results above, I calibrated spring-type and winter-type wheat phenology models for Japanese wheat cultivars and simulated the changes of heading dates of them under different warming scenarios (Chapter 4) and discussed influences of rising temperatures on wheat production in Japan. Based on the results of Chapter 1-4, I finally made proposals of the methodology of model calibration regarding modifying model structures and parameterization methods and proposed several countermeasures for the future climate change (Chapter 5).

Chapter 2

Development of wheat phenology model with vernalization function

Summary

In Japan, spring-type wheat, which does not have a strong vernalization requirement, is mainly cultivated in autumn in the main production area such as Kyusu or Tokai regions except for Hokkaido. Considering this, a wheat phenology development model for spring type cultivars, which included functions of the photoperiod response and the temperature response, has been developed so far in Japan. Meanwhile, winter-type wheat, which has a vernalization requirement, is increasingly planted in warm regions in Japan because it can avoid overgrowth induced by warm winter, and thus developing wheat phenological models that can be applied for winter-type wheat is requiring. Since the conventional model expresses a monotonically increasing growth rate with increasing temperature, the model may incorrectly calculate the daily growth rate when applied to winter-type cultivars with strong vernalization requirement.

In this study, I proposed a new winter wheat development model that combined the above-mentioned conventional model and the vernalization function. The result of the six-fold cross-validation showed the advantage of using the proposed model compared with the conventional model. Although the difference in the accuracy of the two models varied depending on the cultivars, a 0.5-2.5 days improvement of RMSE was found in all wheat cultivars. Specific biased errors were produced when using the conventional model, while the proposed model could improve the bias.

The detail of this chapter was published in the peer-reviewed journal (Publication list: 2).

Chapter 3

Evaluation of parameterization methods on the wheat phenology model

Summary

In this chapter, I evaluated the influences of both model structures and parameterization methods on winter wheat phenology models using three different models and three parameterization methods. The three models tested here were the APSIM-wheat model, the Wang and Engel model, and the sigmoid and exponential function based (SEB) model that I newly proposed in the last chapter. Regarding parametrization methods, the three different approaches were augmented Lagrange multiplier method (ALM), Nelder-Mead method (NM), and Bayesian optimization with Gaussian process (BO), and the influences of model structures and parameterization methods on the accuracy of wheat phenology modeling were investigated. From the result of six-fold cross-validation, the median of the RMSE range was mostly 2–7 days in the test data, which was independent of the training data. Regarding model trueness, the SEB model parameterized by BO exhibited relatively low predictive performance. In terms of precision, the SEB or the Wang and Engel model with BO tended to exhibit a larger RMSE coefficient of variation values than those from other parameterization methods, whereas there were few differences in the APSIM model among parameterization methods. Regarding parameter uncertainty, a higher uncertainty was observed in the combinations of SEB × BO or NM, whereas there were relatively small parameter uncertainties in the APSIM models regardless of the parameterization method. The results of this study clearly show that both prediction and parameter uncertainty is dependent on model structure and parameterization method, and their combination is especially important for models with more parameters.

The detail of this chapter was published in the peer-reviewed journals (Publication list: 1 and 3).

Chapter 4

Influence of the rising temperature under climate change on wheat phenology

Summary

In this chapter, I developed wheat development models for two spring- and three winter-type cultivars in Japan and investigated how their heading dates changed in different warming scenarios when grown at two locations at six different sowing times between October and December. The sigmoid and exponential function based model (SEB model), which is modified in Chapter 2, was used in this study. The SEB model differs from other wheat development models in that the different responses of individual cultivars to temperature can be described by parameters before and after vernalization requirements are satisfied.

As a result, the advancement of the heading date of spring-type and winter-type wheat greatly varied depending on the timing of sowing and growing environments. The earlier the spring-type cultivars were sown, the faster they grew to heading (spring wheat: 6-16 days °C^{-1}; winter wheat: 4-7 days °C^{-1}). In winter wheat, the shortening period from sowing to heading was larger when grown in a relatively cold winter region (below 4 °C during the winter) than when growing in a warmer winter region as warming significantly advance. Also, increased temperatures in spring induced the advancement of heading more than similar conditions in winter. As an adaptation to warming, it was suggested that delaying sowing may be particularly effective for spring type cultivars cultivation. In addition, it was suggested that changing winter type cultivars, which has vernalization requirements, from spring-type wheat can ease the earliness of heading and reduce the risk of frost damages.

The detail of this chapter is under preparation for submitting a peer-reviewed journal (Publication list: 4).

Chapter 5

General Discussion

Summary

In this study, I improved and established the methodology of wheat development model calibration and utilized the established model for understanding how wheat cultivated in Japan can be influenced by the rising temperature. First, the accuracy of predicting the flowering period of wheat was improved by incorporating the function expressing the vernalization requirement of winter wheat cultivars into an existing model used in Japan. Furthermore, three different parameterization methods were evaluated quantitatively and identified which methods were more effective in obtaining stable parameters and prediction accuracy. Finally, the established methodology was used for calibrating five wheat phenology models and utilized them for quantitative investigation of the phenology changes under different rising temperature scenarios, and I proposed countermeasures for the adaptation of wheat production in Japan under the changing environment. In this way, combining meteorological information and information processing techniques can contribute to making efficient decisions in crop production and to understanding the environmental response of crops to future climate change. As the development of sensing technology and bioinformatics makes it possible to collect a wide range of information on crops and their growing environment, it will be increasingly expected to use and analyze this information effectively to address problems related to future agricultural production. This study provides an important case for the use of environmental information and statistical analysis and modeling techniques to obtain information that contributes to efficient crop production management. The integration of information science and agricultural knowledge is expected to become increasingly important in the future development of the agricultural system.

Publication lists

The contents of chapters 2 and 3 partly include the content of published peer-reviewed journals (publication list 1−3), and the content of chapter 4 is under preparation for submitting a peer-reviewed journal (publication list 4).

1. Kawakita, S., Inaba, S., Takahashi, T., Kamada, E., Ishikawa, N., Takahashi, H., Okuno, R., 2019. Evaluation of non-linear wheat development models and optimization methods for their parameter determination. J. Agric. Meteorol. 75, 120–128. https://doi.org/10.2480/agrmet.d-18-00034 (Chapter 3)

2. Kawakita, S., Ishikawa, N., Takahashi, H., Okuno, R., Takahashi, T., 2020. Winter wheat phenological development model with a vernalization function using sigmoidal and exponential functions. J. Agric. Meteorol. 762, 81–88. https://doi.org/10.2480/agrmet.D-19-00042 (Chapter 2)

3. Kawakita, S., Takahashi, H., & Moriya, K. (2020). Prediction and parameter uncertainty for winter wheat phenology models depend on model and parameterization method differences. *Agricultural and Forest Meteorology*, 107998. https://doi.org/10.1016/j.agrformet.2020.107998 (Chapter 3)

4. Kawakita, S., Ishikawa, N., Takahashi, H., Okuno, R., Takahashi, T., Moriya, K.
   The advancement of wheat heading date owing to rising temperatures varies with cultivar type, sowing time, and growing environment (Tentative title).
   (Submitted) (Chapter 4)