博士論文

Optimizing Productivity and Quality of Wheat through Modelling Approach

(モデリングアプローチによるコムギの生産性と品質の最適化)

A Thesis Submitted to the
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in Partial Fulfillment of the Requirements for the Degree of
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By

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Dedicated to my loving family and teachers

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ABSTRACT

Ph.D Thesis submitted to the Department of Global Agricultural Sciences,
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Introduction

Wheat is the second most important cereal crop in Japan. However, the national average wheat yield in Japan (4.1 t ha^{-1}) is lower than that in other major wheat producing countries. In the last decade, per capita consumption of wheat increased by 4.1% while that of the staple food rice decreased by 11%. The self-sufficiency ratio of wheat in Japan is only 13.3%. Therefore, in order to safeguard the food security and maintain agricultural sector, Japanese farmers are subsidized for wheat production through “quality bonus” depending on the grain quality indices including grain protein content (GPC). GPC can be controlled by nitrogen (N) fertilizer management, but it is the most variable factor depending on the soil and climatic conditions and the management practices. Therefore, it is an important matter at both national and farm level to improve the N management of wheat to increase grain yield by maintaining adequate GPC.

Modelling approach with field experiments and proper validation would be useful to predict the yield and GPC under different management options including N application and to provide necessary decision support for the producers to improve wheat productivity.

The present study focused on first, evaluating the interactive effects of nitrogen application at flowering and sowing date on grain yield and GPC of hard and soft wheat varieties, and elucidating the mechanisms of yield and GPC change under late sowing

conditions. Second, integrating that knowledge for the parameterization of two Japanese cultivars (hard and soft wheat) representative of Kanto region in Japan for APSIM (Agricultural Production Systems sIMulator) crop growth model, and validating the APSIM model for the conditions in Kanto area for the optimal sowing conditions and improving the model for late sowing conditions. Third, developing a decision support on optimum nitrogen management using the validated model to improve the wheat productivity for Kanto region. And fourth, extending the same modelling approach to Hokkaido region.

Materials and methods

To study the effect of nitrogen application at flowering time and sowing time interactions three field experiments were conducted from November 2010 to June 2013, at the Institute for Sustainable Agro-Ecosystem Services (ISAS) of the University of Tokyo at Nishitokyo City, Tokyo. The factors of the first experiment were 2 sowing dates and 4 N application level. Those of the second experiment were 1 sowing date and 4 N application level. Those of the third experiment were 4 sowing dates, 3 N application level. N was applied as basal and two splits (split at the time of stem elongation and flowering) in all these experiments. Two hard wheat cultivars, Yumeshiho and Nishinokaori, and two soft wheat cultivars Ayahikari and Nebarigoshi were used for the 2012-2013 experiment and only Yumeshiho and Ayahikari were used for the other two experiments.

Further, to elucidate the mechanisms of yield and GPC change under late sowing conditions, two field experiments were conducted from 2014 to 2016 at the same location. The cultivars Yumeshiho and Ayahikari were used. The 4 sowing dates including very late sowing and 2 levels of N application were tested.

Phenology, dry matter production, LAI, grain yield and GPC data from 2012-2013 field experiment were used to parameterize the APSIM model for Ayahikari and Yumeshiho. Then, APSIM model was validated for phenology, dry matter production, LAI, grain yield and GPC and, soil NO_3 using independent experimental data from 2010-2016. Further, APSIM model was validated for a hard and a soft wheat cultivars representative to Hokkaido using soil and climatic data of the area and crop experimental data from the literature.

APSIM model was improved to be applied under late sowing conditions by integrating an empirical model developed from plant emergence data into APSIM model. Then the improved model was revalidated with data set including both optimum and late sowing conditions.

Scenario analysis were conducted with validated model with 64 N treatments ranged from 0 – 360 kg total N ha^{-1} with different proportion of basal and split applications at standard sowing date by using 55 years daily weather data of Tokyo for the wheat cultivars Yumeshiho and Ayahikari in Kanto region. Similar scenario analysis was conducted for two Hokkaido cultivars, Yumechikara (hard wheat) and Kitahonami (soft wheat), using 30 years weather data to find out economically optimal N application regime.

Results and Discussion

The results of the field experiments suggested that the N management strategy at flowering time for increasing the GPC is suitable under optimum sowing conditions, and the GPC content of both hard and soft wheat sown at optimum timing can be adjusted for fitting into the quality bonus window, by altering the fertilizer application rate at flowering time. The study contributes toward improving our understanding of the effects of split N fertilizer application at the stem elongation and flowering stages, and the effect of sowing time on the grain yield and GPC of both hard and soft wheat grown in volcanic ash soils. This was the first study to report the interactive effect N application at flowering and sowing time for both hard and soft wheat varieties grown in volcanic ash soils.

We demonstrated that the late sowing conditions decreased grain yield and increased GPC of both hard and soft wheat grown in Kanto region. Grain yield reduction by late sowing was mainly caused by reduced number of heads per area, which was mainly caused by the reduced emergence. The lower temperature which the late sown seeds has to face not only delayed the emergence but also reduced the ultimate emergence percentage. The reduction in the ultimate emergence percentage was quantitatively linked to the time required from the sowing to emergence with quadratic function.

Model validation confirmed that parameters derived from the calibration were accurate and these parameters can be used for the prediction of wheat phenology and growth parameters such as yield and GPC. The results showed that RMSE for grain yield was 79.9 and 69.0 g m^{-2} for Ayahikari and Yumeshiho, respectively and that for GPC was 1.8 and 2.4 %. Similarly, validation results for Hokkaido for optimal sowing showed that RMSE for grain yield was 75 and 86 g m^{-2} for Kitahonami and Yumechikara, respectively, and that for GPC was 1 and 0.5 %.

These results are within the range of RMSE in the APSIM model validation studies reported elsewhere.

The results of the scenario analysis indicated that economically optimum rate of total N application for Yumeshiho (hard wheat) and Ayahikari (soft wheat) in Kanto region was both 280 kg N ha^{-1} although the proportion of the split application was different. With these optimum N treatments, the producers can obtain by 85 and 146 % higher median gross margin for Yumeshiho and Ayahikari, respectively, compared to that can be obtained with current fertilizer recommendations. The simulation results showed that optimal N application scheme tended to fluctuate to some extent from year to year due to the climate variation. However in the years with normal precipitation it was at or closer to the optimal N scheme.

In the scenario analysis in Hokkaido, the economically optimum rates of total N application for Yumechikara (hard wheat) and Kitahonami (soft wheat) were 280 and 160 kg N ha^{-1} respectively. With these optimum N treatments, it was simulated that the producers can obtain by 29 and 20.5 % higher median gross margin for Yumechikara and Kitahonami, respectively. The simulation results showed that yearly optimal N application scheme tended to be relatively stable during the 30 years' period.

Conclusions

The purpose of this study was to optimize productivity and grain protein content of wheat through modelling approach. N management was focused as the main agronomical option. The strategy to cope with the late sowing issue was also tested with the same approach. It was demonstrated that, by increasing total rate of N application, current yield level region can be increased particularly in Kanto region to the level similar to that of other high yielding countries with reasonably appropriate GPC, and thereby profitability of the producers could be increased. This is the first study to use APSIM model for wheat management in Japan. The section of the model improvement also contains originality, with which the model better fit to the late sowing situation by incorporating the algorism of reducing the plant number at low temperature. For the future research, it was suggested to extend and test this modelling approach to other regions such as Kyushu.

ABBREVIATIONS

ANOVA; Analysis of variance

APSIM; Agricultural Production Systems Simulator

GPC; Grain protein content

LAI; Leaf area index

LSD; Least significant difference

ME; Modelling efficiency

N; Nitrogen

RMSE; Root mean square error

RRMSE; Relative root mean square error

Chapter 1

Introduction

1.1 Wheat (*Triticum aestivum*) the second most important cereal crop in Japan

Wheat is the second highest energy source in the diet of Japanese, after rice (FAO, 2014). People consume wheat products such as bread, pasta, Japanese noodles (udon), and Chinese noodles (ramen) almost on a daily basis. The per capita consumption of wheat has been increased in Japan since 1950s with several fluctuations over the time owing to the declining happened with the increase in rice production, increased in consumption of animal products between 1954 and 1957 and between 1981 and early 1990s respectively (Smil and Kobayashi, 2012). Lately, per capita, wheat consumption increased by 4.1% in last decade while that of the staple food rice decreased by 11.1% (USDA, 2017). At present, wheat is ranked second after maize amongst the import commodities in food and agriculture category, in Japan (FAO, 2014). Although Japan has favourable wheat-growing conditions, with sufficient annual rainfall of 840–2800 mm, the national average yield in Japan (4.1 t ha^{-1}) is lower than that in other major wheat producing countries in Europe, such as France, Germany, Netherlands and UK (6.8, 8.1, 8.8 and 8.5 t ha^{-1}, respectively). The largest wheat producing region in Japan is Hokkaido (64.7%) followed by Kyushu (13.8%) and Kanto (8.1%).

1.2 Self-sufficiency and government intervention for improving wheat production in Japan

The self-sufficiency ratio of wheat in Japan is a mere 13.3% (FAO, 2014) and the production is not sufficient to meet the domestic requirement. Therefore, in order to safeguard the food security and maintain agricultural sector, Japanese government is implementing a subsidy system for wheat. Under this subsidy system, producers are given an acreage subsidy for each hectare of land that produced wheat (115,220 JPY ha^{-1}) and the quality bonus is given for the produced wheat. In this quality bonus subsidy system, the producers can receive a quality bonus payment from the government based on four grain quality parameters, i.e., grain protein content (GPC), falling number, ash content and bulk density.

Table 1.1 shows the quality bonus scheme offered based on the GPC (MAFF, 2014). According to this scheme, there are three levels of ranking for quality bonus. Farmers can obtain maximum quality bonus if they can attain the level of GPC required for ranking A. In other countries as well (e.g. US), the premium prices for wheat are determined by the GPC (Olmos et al. 2003). Wheat varieties in Japan are classified into two groups, i.e., hard wheat (used for bread) and soft wheat (used for noodle), depending on the grain quality (mainly protein content) (Nakano et al. 2008).

Table 1. 1 Quality bonus offered based on the GPC

Wheat type	**Rank**	**Required GPC (%) range**	**Quality bonus (¥ t^{-1})**
Hard Wheat	A	11.5 - 14.0	150,000
	B	10.0 - 11.5 and 14.0- 15.5	141,667
	C	< 10.0 and 15.5 <	118,667
Soft Wheat	A	9.7 - 11.3	107,500
	B	8.5 - 9.7 and 11.3 - 12.5	99,157
	C	> 8.5 and 12.5 <	76,333

1.3 Nitrogen management to achieve yield gaps and GPC goals

Among these quality indices, grain protein content (GPC) is the most variable, as it depends on the soil and climatic conditions as well as the management practices. It has been widely reported that wheat GPC is influenced by the climate, cultivar, nitrogen (N) application rate, N application timing, seeding rate, soil fertility, and the interactions among these factors (Lopez-Bellido et al., 2005; Garrido-Lestache et al., 2004; Gauer et al., 1992; Sato et al., 1992; Rao et al. 1993; Nakano and Morita 2009, Nakano et al. 2008). In addition, there is usually a negative genetic correlation between the grain yield and GPC (Triboi et al., 2006; Asseng and Milroy, 2006; Kibite and Evans, 1984; Loffler, 1985; Selles and Zenter, 2001; Fowler, 2003; Triboi and Triboi-Blondel, 2002), which makes it challenging to increase the yield while maintaining the GPC within the target range (Triboi et al., 2006).

Recent research has attested that the GPC can be controlled by N application at the flowering stage, while N application at the stem-elongation stage affects the grain yield (Nakano and Morita 2008; Woolfolk et al., 2002; Fischer et al., 1993; Yoshida et al., 2008; Shimazaki and Watanabe, 2010; Takayama et al., 2006; Stark and Tindall, 1992; Zebarth and Sheard, 1992; Peltonen, 1993; Bly and Woodard, 2003; Rutkowska, 2009; Knowles et al., 1994; Rawluk et al., 2000). However, the effectiveness of split N application at flowering for improving the GPC depends on the soil type, and therefore, the control of GPC solely by split N application is difficult (Karathanasis et al., 1980; Sato et al., 1992; Nakatsuji, 2003).

1.4 Importance of soil type

Despite the availability of the improved cultivars that has a potential to produce grains of appropriate protein content than standard cultivars still, the expected results cannot be obtained in the farmers' field due to the effect of climate variation and soil characteristics. For example, the grain quality of wheat cultivar Minaminokaori has not yet met the required protein content as a result of lower nitrogen uptake by the wheat plant due to the shorter growing season in western part of Japan owing to warmer climate and relatively high precipitation (Taya, 2001). Soils of the western part of the Japan are generally mineral soils and their nitrogen supplying capacity is low. Therefore, farmers in this area can increase the grain protein content by a second split application of nitrogen fertilizer.

Volcanic ash soils, one of the major soil types in Japan (Shoji and Takahashi, 2002; Nanzyo, 2002), are also important soils for wheat production in Japan. Hokkaido, the largest wheat-growing prefecture in Japan, has a high percentage (40%) of volcanic ash soils (Shoji and Takahashi, 2002), while the Kanto region, the third-largest wheat growing area, is nearly composed entirely of volcanic ash soils except alluvial soils along the rivers.

Volcanic ash soils are among the most productive soils in the world for agriculture and forestry, and usually have their colloidal fraction dominated by Al-humus complex or allophane/imogolite in humid weathering environments (Ugolini and Dahlgren, 2002). Organic matter tends to be highly accumulated in volcanic ash soils, owing to their stabilization by the formation of Al-humus complex. Non-crystalline materials and humus contribute to the unique chemical and physical soil properties of volcanic ash soils, such as high water-holding capacity, variable charge, high phosphorus retention, low bulk density, high friability, and high rate of formation of stable soil aggregates (Soji et al., 1993). Some of these properties support a higher productivity of crops through a better retention of nutrients and water, compared with other soil types when the disadvantage, high P fixing capacity, is corrected by higher phosphorus application. The native nitrogen-supplying capacity in volcanic ash soils is higher than that in other soils and is further enhanced by the application of N fertilizers, which stimulates the mineralization of the native soil nitrogen (Eneji et al., 2002).

Therefore, if the temperature is high enough, soil releases higher amount of nitrogen and coincidence of such condition with the anthesis period of the crop will result in very high grain protein content. Otherwise, the grain protein content becomes lower. Thus, farmers are facing a difficult situation in achieving expected grain protein content.

1.5 Importance of sowing time

In the case of winter wheat, the plants sown in the optimal period, better germination rates, good crop establishment (Farroq et al., 2008), and longer vegetative period can be expected, together with a better root growth, compared with the late-sowing conditions (Barraclough and Leigh, 1984). However, delayed sowing tends to reduce the grain yield while increasing the GPC typically (Singh and Jain, 2000). Late planting is a major limitation to wheat productivity in many regions of South Asia that have a rice-wheat cropping system (Hobbs et al., 1994) and in other temperate and subtropical countries. For the main target area of this research, Kanto area in Japan, the interaction between the sowing time and the effect of fertilization at flowering time on GPC is an area that has not been duly addressed in literature especially in relation to the wheat grown in volcanic ash soils.

1.6 Importance of a decision support for wheat cultivation

Understanding the interactions between crop, soil and climate are vital to make decisions on optimum nitrogen application and other agronomic practices towards achieving higher yield and appropriate grain protein content for wheat grown under optimal as well as late sowing conditions. From these reasons, the comprehensive decision support system for the proper nitrogen management is awaited in wheat production in Japan to narrow the existing yield gaps while maintaining expected GPC required for higher quality bonus for wheat sown under optimal sowing conditions and to minimize the yield losses under late sowing conditions.

So far numerous field experiments have been conducted for the above purposes. But there are several limitations in such field researches. They are:

1. Due to the spatial variability in climate and soil characteristics, the results of filed experiments are site specific. Existing literature also reported that the results of the field experiments are season-specific, too (e.g. Spiertz and Ellen, 1978; Spiertz and Van de Haar, 1978; Ellen and Spiertz, 1980; Chaney, 1990; Darwinkel, 1998; as cited in Asseng et al., 2000).

2. Requirement of the longer duration to obtain the reasonable results; multiple year trials are needed to conclude any fertilizer or crop related recommendations.

3. Multiple experiments with different trial combinations are needed to find out any optimum conditions (e.g., optimum rate and timing for nitrogen application).

Therefore, use of crop growth models is one of the best alternative options available and a properly validated crop growth model is a good decision support system for both farmers and scientists to make economically viable decisions on management practices and research perspectives. Existing reports also explain the use of crop models to optimise management practices under variable environments (Van Keulen and Seligman, 1987; Stapper and Harris, 1989; Keating et al., 1991; Meinke et al., 1993; Savin et al., 1995; Thornton et al., 1995; Asseng et al., 1998 as cited in Asseng et al., 2000). But before coming up with any recommendations based on a crop model, the model should be properly validated for the local condition. APSIM (The Agricultural Production Systems Simulator) is one of such crop growth models that has successfully been used in many other countries to simulate wheat growth (e.g., Asseng et al., 2000; Wang et al., 2013; Zang et al., 2012; Mohanty et al., 2012 ; Balwinder-Singh et al., 2011). Table 1.2 shows the different situations of using simulation models for decision support.

Table 1.2 Use of simulation models as a decision support

Type of decision support	Name of the model	Reference
Decision support for Australian dry land farming (commercial crops)	APSIM	Carberry (2009)
Decision support for wheat management in subtropical Australia	WHEATMAN	Wood ruff (1992)
Decision support on wheat N fertilization based on the date of N deficiency	Azodyn	Jeuffroy and Recous (1999)
Climate change impact on crop production	DSSAT	Hoogenboom et al. (1995)
Decision support for irrigation and water management	CADSM	Prajamwong et al. (1997)
Wheat disease management	Foliar disease model	Audsley et al. (2005)
Assessing nitrogen leaching losses from arable land	SOILNDB	Johnsson et al. (2002)
N application decision support for corn	Empirical model and online decision support tool	Gramig et al. (2017)

1.7 APSIM (The Agricultural Production Systems Simulator)

1.7.1 An overview

APSIM (Agricultural Production Systems sIMulator) is one of the advanced cropping system model that comprised of different modules enabling to simulate systems that cover a range of plant, animal, soil, climate and management interactions (Keating et al, 2003).

1.7.2 APSIM-Wheat module

Simulation is carried out in a daily time-step on an area basis. Weather (temperature, radiation, precipitation) data should be provided externally. The initial content of water and inorganic nitrogen at different soil layers are required as input and also the crop management information should be provided for the initialization of the simulation.

Soil water and nitrogen uptake data from the wheat module is disseminated on daily basis to the soil water and nitrogen modules. Apart from that, information on crop cover is transferred to the water balance module for the calculation of evaporation rates and runoff. At the time of crop harvest, information on the amount of wheat stover and root residues are passed to the modules of surface residue and soil nitrogen, respectively. Phenological development, leaf area growth, biomass and nitrogen concentration of leaves, stems, roots, and grains, grain size, grain number are simulated in the wheat module on a daily basis.

The phenology is comprised of 11 stages. They are sowing, germination, emergence, end of juvenile, floral initiation, flowering, start of grain filling, end of grain filling, maturity, harvest rips, and end crop. The length of each stage is determined by a fixed thermal time (APSIM wheat module document). Sowing to germination is determined by soil water availability in seeded layer and germination to emergence phase is comprised of two sub phases from which the first has a fixed thermal time and the thermal time for the second is calculated with sowing depth and thermal time required for unit elongation.

The daily biomass accumulation is calculated as a potential biomass accumulation, resulting from radiation interception. This potential biomass accumulation is limited by soil water deficiency. Radiation interception is calculated from leaf area index (LAI) and the light extinction coefficient. Radiation use efficiency is a function of growth stages and each growth stage has fixed value of radiation use efficiency.

For the biomass partition, wheat plant is divided into four components. They are root, head, leaf, and stem. Stem is regarded as uni-clum in APSIM wheat and number of tillers are also represented by nodes on main stem. Head is divided into grain and pod (correspond to spike without the grain).

The number of grains per plant is determined by the stem weight at anthesis with a cultivar specific value named grains per gram stem. The grain demand is calculated in the growth phase from flowering to end of grain filling. The rate of grain filling is affected by daily mean temperature. Grain nitrogen demand starts at anthesis. The original GPC routine simulated GPC as a function of independent dry matter and N accumulation into the grain. After Asseng et al. (2002) an upper boundary of daily protein transfer to the grain is set to 4% N (22.8% GPC), and a lower boundary is set at 1.23% N (7% GPC) to constrain GPC simulations under very high and very low input conditions.

N stress phase begins before 30% floral initiation to finish at the harvest ripe. N stress is applied on biomass accumulation, leaf appearance and expansion, and grain filling in the current version of model. N stress on grain filling affects the biomass demand of grain and the N demand of grain. In the current version of APSIM wheat model, effect of phosphorous stress is not dealt with.

1.8 Uses of APSIM model in wheat crop management studies including nitrogen management

There have been very few reports on the application of crop growth models for wheat under Japanese conditions (e.g., Kuwata, 2013; Seino, 1995; Honda et al., 2014). No report on the application of APSIM model under Japanese conditions was published so far. The literatures on the application of APSIM crop growth model for wheat are, however, found in other countries.

Asseng et al. (1998, 2000) tested the performance of APSIM model in Western Australia and the Netherlands. Their studies in Western Australia showed that APSIM Nwheat model was able to simulate the wheat crop growth and yield reasonably. They, however, did not recommend the version of the model they tested for grain protein studies and therefore another study was reported later for improving the model for better GPC prediction (Asseng et al., 2002). In the Netherlands, APSIM Nwheat showed better performance to simulate the interactions between a wide range of nitrogen fertilizer applications and soil nitrogen dynamics, crop N uptake, crop growth and phenology, grain yield and grain protein content.

Asseng et al. (2000) reported that APSIM simulations appropriately reflected the differences in LAI with different N treatments however, LAI was over-estimated between end of tillering and flag leaf stage.

The climate and soil type varies spatially. Thus, wheat yield also changes from place to place with different crop management practices such as cultivars, sowing time, plant density, and irrigation and fertilizer application. As I mentioned earlier, it is difficult to capture such effects via field experiments only. Zhang et al. (2012) reported such study using APSIM with three sowing dates, two to three crop varieties, and three planting densities at three ecological sites in the Northern China Plain. Their results showed that the model could capture a larger part of the variation in phenology, biomass and crop yield for the same variety across the sites.

But, errors in simulation in phenology and yield were increased with delay in sowing date and with decreased planting density. According to their study, the model showed a better performance in a warmer site than a colder site. Another study was reported by Chen et al. (2010) on capturing the crop productivity responding to inter-annual climate variability and irrigation water supply with long term crop yield data under various irrigation water supply in Northern China Plain for wheat and maize double cropping systems. Their results show that APSIM model is capable to simulate growth and yield of wheat and maize in a double cropping systems. Predictions of soil water and evapotranspiration were also good. They mentioned that it was necessary to change the low temperature threshold for leaf area damage induced by low temperature, the temperature response of crop phenologies, and temperature response of radiation use efficiency (RUE) for the better simulation of the winter wheat production

Further, Asseng et al. (2000) were able to derive the economic and environmental optima in winter wheat under the Netherlands conditions; N application up to 140 kg N ha^{-1} in February (period at which crop growth starts after the winter), 90 kg N ha^{-1} between tillering and beginning of stem elongation and 40 kg N ha^{-1} at flag leaf stage resulting in a median of 8.5 t ha^{-1} grain yield, 14.0% grain protein and 13 kg N ha^{-1} soil residual N after the harvest. Therefore APSIM has shown its capacity to be used as a decision support system upon the validation.

This is what exactly needed in Japanese wheat production systems. Therefore, in this study field experiments were conducted to understand the effect of N application at flowering time and sowing time interactions for both hard and soft wheat and to understand the mechanism for yield change under late sowing conditions. Then, the data from the field experiments were used to parameterize and validate the APSIM model for Kanto area in Japan to conduct scenario analysis with various N application scheme with simulation study to find out the economically and environmentally optimum N application regime for winter wheat.

Further, with the use of secondary data (published data) from Hokkaido, the possibility of applying similar approach to other regions in Japan were tested.

As reported in the literature, APSIM model performances were not good at late sowing and under low temperature conditions (Zhang et al., 2012) and therefore, there is a necessity of improving the APSIM wheat model to capture the effect of late sowing and low temperature on wheat growth by which model prediction to be improved.

1.9 The purpose of the study

The purpose of this study is to develop a modelling approach in combination with field experimental knowledge and crop modelling to improve the wheat productivity and quality (hard and soft wheat) in Japan. Hokkaido and Kanto regions are selected for the study together which account for 74.8% wheat production in Japan. Most part of these regions comprised of volcanic ash soils which has higher indigenous N supplying capacity. Hence, N management need to be done carefully to increase the grain yield while maintaining the GPC content at standard levels. With this background, N management is considered as the main agronomical technology. In addition to that, the late sowing, which is a prevalent condition in Kanto region affecting the wheat productivity is also considered to evaluate its effects with N management.

With respect to the thesis outline, Chapters 2 and 3 consist of the knowledge from field experiments regarding the effect nitrogen application at flowering time and sowing time interactions on grain yield and GPC of hard and soft wheat grown in volcanic ash soils and, effects of late sowing on yield, yield components and seed emergence at low temperature for winter wheat in Kanto region, Japan. Chapters 4 and 5 are about the model application: parameterization and validation of APSIM model and developing a model improvement for late sowing conditions for Kanto region. Chapter 6 focuses on scenario analysis using validated model to elucidate economically optimum N management scheme to improve the wheat productivity in Kanto region, Japan and, Chapter 7 consists of validation of APSIM model for Hokkaido region and scenario analysis to elucidate economically optimum N management scheme.

Chapter 2

Effect of sowing time and N application at flowering on grain yield and GPC of hard and soft wheat grown in volcanic ash soils in Kanto area

2.1 Introduction

To increase the self-sufficiency of wheat in Japan, the Japanese government is offering subsidy for wheat production in the form of "quality bonus", which depends on its grain-quality indices. In this system, the producers receive a special payment from the government based on four grain-quality indices: grain protein content (GPC), falling number, ash content, and bulk density.

Among these quality indices, GPC is the most variable, as it depends on the soil and climatic conditions as well as the management practices. It has been widely reported that wheat GPC is influenced by the climate, cultivar, nitrogen (N) application rate, N application timing, seeding rate, soil fertility, and the interactions among these factors (Lopez-Bellido et al., 2005; Garrido-Lestache et al., 2004; Gauer et al., 1992; Sato et al., 1992; Rao et al., 1993; Nakano and Morita, 2009, Nakano et al., 2008).

Wheat varieties in Japan are classified into two groups, i.e., hard wheat (used for bread) and soft wheat (used for noodle), depending on the grain quality (mainly protein content) (Nakano et al. 2008) (Table 1.1). The required grain N concentrations for the hard wheat and the soft wheat are 2.3–2.8% and 1.9–2.3%, respectively. As for GPC, the range is 11.5–14% for hard wheat and 9.7–11.3% for soft wheat (MAFF, 2014). Wheat producers in Japan can obtain the highest quality bonus (rank A) if the GPC falls into this range.

Recent research has attested that the GPC can be controlled by N application at the flowering stage, while N application at the stem-elongation stage affects the grain yield. However, the effectiveness of split N application at flowering for improving the GPC depends on the soil type, and therefore, the control of GPC solely by split N application is difficult (Karathanasis et al., 1980; Sato et al., 1992; Nakatsuji, 2003).

The interaction between the sowing time and the effect of fertilization at flowering time on GPC is an area that has not been duly addressed in the literatures especially in relation to the wheat grown in volcanic ash soils.

The purpose of the study of this chapter was to test the applicability of flowering-time N application in volcanic ash soil, in the context of late-sowing conditions, for increasing the GPC, and to examine the possibility of introducing other varieties to stabilize the yield and GPC, even in late-sowing situations.

2.2 Materials and methods

2.2.1. Experimental site

Field experiments were conducted at the Institute for Sustainable Agro-Ecosystem Services (ISAS) (35°44′N, 139°32′E), University of Tokyo at Nishitokyo City, Tokyo. The experimental site is located in the Kanto plain, where the volcanic ash soil, classified as Typic Melanudand by USDA soil taxonomy, and Andosol by FAO soil classification, is dominant. The soil layer from the surface to 30 cm depth was Kuroboku andisol (Clay loam, with bulk density 0.73–0.78 g cm^{-3}), and from 30 cm to 100 cm depth was Tachikawa loamy andisol (Loam, with bulk density 0.41–0.77 g cm^{-3}) (Table 2.1). The initial soil NO_3 and NH_4 content of 0-15 cm top soil layer before the fertilization in Oct. 2010 were 11.9 and 19.8 mg N kg^{-1}, respectively. They, however, decreased to 3.3 and 8.3 mg N kg^{-1} respectively in Nov. 2012 (data not shown). The NO_3^- and NH_4^+ in the soil was extracted with H_2O and 2N KCl respectively, and their concentration were measured by ion selective electrodes (Thermo Fisher Scientific, Waltham, USA). The average annual precipitation was 1530 mm and the average annual temperature was 16.5 °C (minimum and maximum monthly averages were 6.2 °C and 27.8 °C, respectively).

Table 2.1Soil characteristics

Soil layer	Texture	Bulk density (g cm^{-3})	C/N*	Volumetric water content (%) at		
				Saturation	Field capacity	Permenant wilting point
Top soil - Kuroboku	Clay loam					
0–15 cm		0.73	13.7	48.2	41.9	31.6
15–30 cm		0.78	13.1	45.7	42.0	31.8
Sub soil - Tachikawa loam	Loam					
30–45 cm		0.77	13.8	46.4	44.7	33.4
45–60 cm		0.45	13.8	62.4	57.7	48.7
60–80 cm		0.41	14.5	64.5	60.2	52.4
80–100 cm		0.45	14.5	62.1	58.3	51.6

* (Kato T, 2003)

2.2.2. Plant materials

We used four wheat varieties, Yumeshiho, Ayahikari, Nishinokaori, and Nebarigoshi; these are the recommended varieties for the Kanto area (Yumeshiho and Ayahikari), Western region (Nishinokaori), and Northern region of the main island (Nebarigoshi). Yumeshiho is a hard wheat variety with a high flour yield and good bread-making quality. Yumeshiho has a shorter culm length and is moderately resistant to leaf rust and wheat yellow mosaic virus (Kiribuchi-Otobe et al., 2009). Ayahikari is an early-maturing, high-yield soft wheat variety, which has a low amylose content that helps produce smooth noodles. It is also resistant to leaf rust and wheat yellow mosaic virus (Yoshida et al. 2001). Nishinokaori is an early-maturing hard wheat variety, which has a higher GPC than the other varieties in the region, but has a slightly lower yield. It has a shorter culm length and is more resistant to lodging than the other varieties in this region (Kawase, 2009, Taya et al., 2003). Nebarigoshi is a soft wheat variety, but is also considered as a dual-purpose variety, due to its good bread-making quality (Taya et al., 2003).

2.2.3. Experiment 1: Effect of N application at flowering time (2010–2011 and 2011–2012)

Experiment one was conducted to see the effect of N application at flowering time in hard and soft wheat.

(1) Experimental design and treatments

The experiment comprised two cropping seasons, i.e., 2010–2011 and 2011–2012. The experimental design was split-plot in 2010–2011 with two sowing dates (Nov 2 and Dec 1) as the main factor, two wheat varieties (Ayahikari and Yumeshiho) as a sub factor, and four levels of N application (0, 80, 110, and 140 kg N ha^{-1}) as a sub-sub factor (Table 2.2). The 2011–2012 experiment used a split-plot design with the same two varieties as the main factor, and the same N treatments as a sub-factor, with a single sowing date (Nov 16**)**. In both the seasons, the experiment was conducted with three replications.

Table 2.2 Rate of nitrogen fertilizer application (kg N ha^{-1})

	Year	**Treatment**	**Total N**	**Basal**	**First split (at stem elongation)**	**Second split (at flowering)**
Experiment 1	2010–2011	N0	0	0	0	0
	and	N1	80	60	20	0
	2011–2012	N2	110	60	20	30
		N3	140	60	20	60
Experiment 2	2012–2013	N0	0	0	0	0
		N1	80	40	20	20
		N2	150	80	40	30

(2) Crop management

N application was split into three stages: as basal, at the stem elongation stage, and at flowering (Table 2.2). Ammonium sulphate was used as the N fertilizer. The plot area was 24 m^2 and 48 m^2 in 2010–2011 and 2011–2012, respectively. In both years, the plots were supplied with a PK fertilizer in the form of basal application at a sufficient level (P_2O_4 100 kg ha^{-1} and K_2O 75 kg ha^{-1}). Sowing was conducted using a non-till drill seeder, with 19 cm row spacing. The sowing density and depth were 80 kg ha^{-1} and 25 mm, respectively. The standard sowing window of the region is early-to-mid November.

(3) Measurements

At physiological maturity, 1 m × 0.95 m area of each plot was sampled for the analysis of grain yield, total biomass, and harvest index. The dry matter and seed dry weight were determined by drying the samples at 80 °C until a constant weight was achieved. The grain N content was analysed by the dry combustion method (Elimental Analyzer Flash EA 112, Thermo Electron Corporation, Delft), and a conversion factor of 5.7 was used to derive the GPC from the N content. The grain yield and GPC results were corrected by adjusting the moisture content to be 12.5% and 13.5%, respectively.

2.2.4. Experiment 2: Interaction effects of varieties, sowing dates, and fertilizer application rates (2012–2013)

Experiment two was conducted to see the effect of the timing of sowing on grain yield, GPC and interaction effects of varieties, sowing dates and fertilizer application

(1) Experimental design and treatments

Experiment 2 comprised one field experiment conducted in the 2012–2013 cropping season. The experimental design was split-split plot design, with four wheat varieties (Ayahikari, Yumeshiho, Nishinokaori, and Nebarigoshi) as main factor, three N levels (0, 80, and 150 kg N ha^{-1} in total) as a sub factor, and four sowing dates (Oct 17, Nov 8, Nov 29, and Dec 19) as a sub-sub factor.

(2) Crop management

N application was split into three stages: as basal, at the stem elongation stage, and at flowering. Ammonium sulphate was used as the N fertilizer (Table 2.2). The plot area was 36 m^2. The variety Nebarigoshi was not sown in the Oct 17 sowing due to the unavailability of the seeds. Other crop management practices were the same as that of Experiment 1 (see 3 (2)).

(3) Measurements

At flowering, 0.5 m × 0.57 m area of each plot was sampled for measuring the total biomass and leaf area index (LAI). The phenology was observed every week throughout the experiment. Measurements and analysis conducted at physiological maturity were the same as in Experiment 1. Yield components were also analysed.

2.2.5. Statistical Analysis

Experimental data for each year was subjected to analysis of variance (ANOVA) and the means were compared with Tukey's test at $P<0.05$, using R statistical analysis software (R Development Core Team, 2008).

2.3 Results

2.3.1. Weather conditions

Figure 2.1 shows the weather conditions for the three study seasons at the experimental site, and the average of the past 30 years (1981–2010) at the nearest weather station (Tokyo District Meteorological Observatory, 22 km away). Considering the total precipitation during the wheat-growing season, 2011–2012 was the wettest (1225 mm) followed by 2010–2011 (1138 mm) and 2012–2013 (899 mm). The average over the last 30 years was 1157 mm. The precipitation distribution pattern was relatively consistent among the three seasons. However, the precipitation during March and April was low in the 2010–2011 and the precipitation in early spring (March), when the maximum temperature starts increasing rapidly, was higher in 2012 compared to other years. The variation in temperature during the three growing seasons was also similar. The minimum temperature dropped to nearly zero in December in these three years.

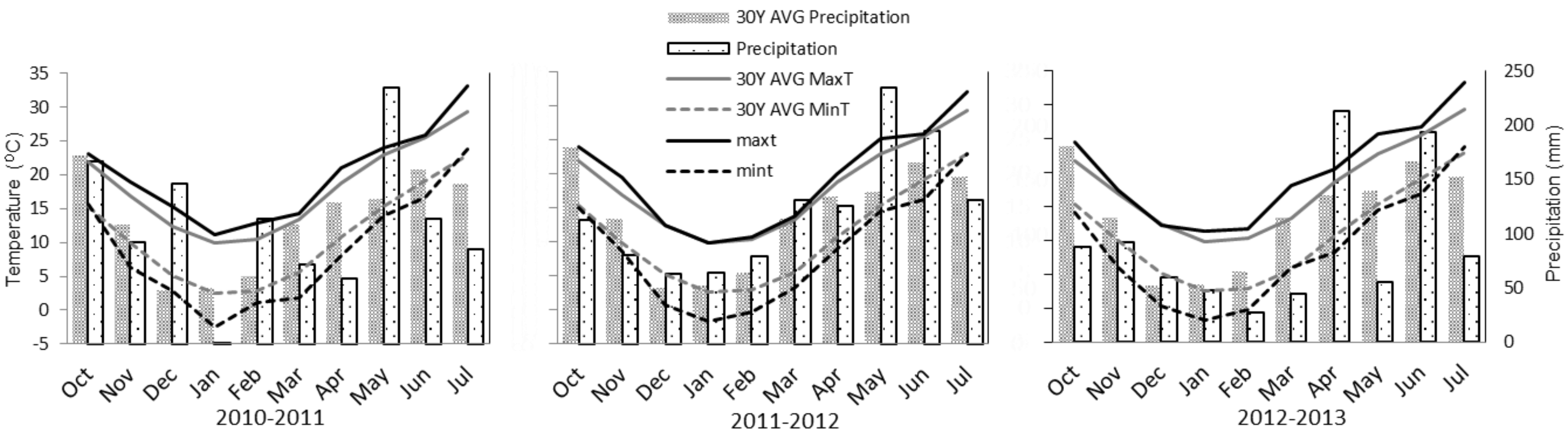


Figure 2.1 Monthly average of daily maximum and minimum temperatures and monthly precipitation for three cropping seasons of the experiment, and their 30-year average at the Tokyo Meteorological Station, Tokyo, Japan.

2.3.2. Experiment 1: Effect of N application at flowering time (2010–2011 and 2011–2012)

N application at both sowing and stem elongation stages tended to have increased the grain yield and the total dry weight at physiological maturity (*cf*. N0 and N1) for both hard and soft wheat varieties during the two seasons, although the effect was clearer for total dry weight in hard wheat (Table 2.3). N application at flowering, however, did not have a significant effect on the yield and total dry weight at maturity (*cf*. N1, N2, and N3) except for one case (total dry weight increase at Nov 2 sowing group for Ayahikari in 2010-2011 (*cf*. N1 and N2)). Overall, the effect of N application was significant when all the N treatments including N0 were compared ($P<0.001$), but for the grain yield and total dry weight at maturity it was not significant when only N1–N3 were compared. The effect of sowing time × variety interaction was significant for the total dry weight ($P<0.05$). When the analysis of variance was conducted excluding N0, there were significant effects of sowing time and sowing time × variety interaction ($P<0.05$) in yield. There were no remarkable differences in the harvest index across the sowing time and varieties.

Table 2.3 Effect of N application rate (split) and sowing time on the grain yield, GPC, total dry weight at maturity, and harvest index in 2010–2011 and 2011–2012

Year	Sowing time	Fertilizer treatment	Yield (g m^{-2}) (12.5% moisture)				GPC % (13.5% moisture)				Total dry weight (g m^{-2})				Harvest Index	
			Ayahikari		Yumeshiho		Ayahikari		Yumeshiho		Ayahikari		Yumeshiho		Ayahikari	Yumeshiho
2010-2011	2-Nov	*N0* 0–0–0	373	b	239	b	8.9	b	10.2	b	667	b	490	b	0.49	0.42
		N1 60–20–0	501	a	498	ab	9.5	b	11.4	b	884	b	848	a	0.50	0.51
		N2 60–20–30	646	a	475	ab	11.9	a	12.8	b	1082	a	933	a	0.52	0.44
		N3 60–20–60	634	a	619	a	12.4	a	14.2	a	1091	a	1077	a	0.51	0.51
	1-Dec	*N0* 0–0–0	194	a	250	b	12.1	b	11.5	b	318	a	437	b	0.53	0.50
		N1 60–20–0	350	a	533	a	13.4	b	13.3	a	329	a	856	a	0.50	0.54
		N2 60–20–30	417	a	474	a	13.7	b	14.7	a	677	a	798	a	0.54	0.52
		N3 60–20–60	438	a	496	a	14.2	a	15.2	a	758	a	776	a	0.49	0.56
2011-2012	16-Nov	*N0* 0–0–0	229	b	193	b	11.7	b	9.4	c	340	b	317	b	0.59	0.54
		N1 60–20–0	447	a	408	a	10.7	b	10.0	c	677	a	626	a	0.58	0.57
		N2 60–20–30	425	a	424	a	11.2	b	12.8	bc	636	a	669	a	0.59	0.55
		N3 60–20–60	489	a	445	a	15.6	a	17.1	a	698	a	705	a	0.61	0.55
	ANOVA															
	Sowing (A)		NS	(*)			NS	(NS)			**	(NS)			NS	(*)
	Variety (B)		NS	(NS)			NS	(*)			*	(NS)			NS	(NS)
	Fertilizer (C)		***	(NS)			***	(***)			***	(NS)			NS	(NS)
	A x B		NS	(*)			NS	(NS)			*	(*)			NS	(NS)
	A x C		NS	(NS)			***	(***)			NS	(NS)			NS	(NS)
	B x C		NS	(NS)			*	(NS)			NS	(NS)			*	(NS)
	A x B x C		NS	(NS)			NS	(NS)			NS	(NS)			NS	(NS)

Fertilizer treatment denoted by same letters do not differ significantly (P<0.05, Tukey's test)

***,**,* : significant at P < 0.001, P < 0.01 and P < 0.05 (within brackets are results excluding 0-0-0 N treatment)

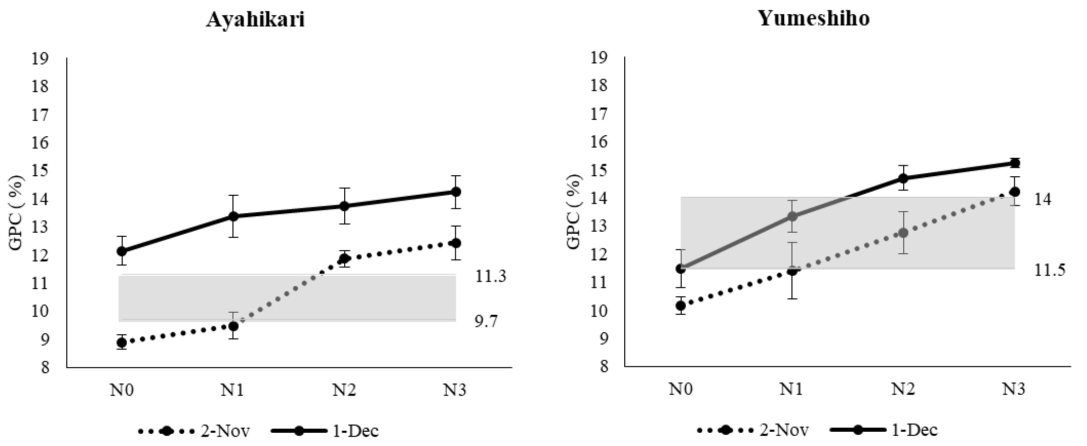
On the other hand, the GPC increased significantly with increasing N application at flowering (*cf*. N1, N2, and N3), but not with N application at both sowing and the stem elongation stages (*cf*. N0 and N1) (Table 2.3). The only exception was the Yumeshiho sown on Dec 1 in 2010 where GPC was increased by the N application at stem elongation stage. Sowing time × fertilizer interaction ($P<0.001$) and variety × fertilizer interaction ($P<0.05$) were significant with respect to GPC. When the analysis of variance was conducted excluding the zero N treatment (N0), there was a significant effect of variety as well for the GPC ($P<0.05$), but the variety × fertilizer interaction was not significant. Figure 2.2 shows that 30 kg of N application at flowering time (N2) increased the GPC of Yumeshiho, pushing it into the supreme (rank A) quality bonus window, at both Nov 2 and Nov 16 sowing, while the GPC of Ayahikari was almost entered in this window under both N1 and N2 at the Nov 2 and Nov 16 sowing. Supply of 60 kg N at flowering time (N3) tended to increase the GPC beyond the quality bonus window for both varieties, although the increase was lower for Nov 2 sowing than for Nov 16 sowing. The late-sowing group (Dec 1) tended to have a higher GPC compared with other sowing group under zero N supply (N0) for both varieties, and the N application at flowering time tended to result in an even higher GPC, above the quality bonus range, in both varieties. Thus, the GPC content of Ayahikari and Yumeshiho sown at the optimum timing are amenable, for reaching the quality bonus window through fertilizer application. Therefore, application of N at the time of flowering is shown to be effective more under optimum sowing conditions but not under late-sowing conditions.

2.3.3 Experiment 2: Interaction of variety, sowing date, and fertilizer application (2012–2013)

(1) Phenology

As shown in Figure 2.3, both the flowering and the maturity were delayed by late sowing. In fact, the duration from sowing to maturity was shorter by 15–35 days with late sowing than with standard sowing (Nov 8). The duration from sowing to flowering was also reduced by 16–31 days for Ayahikari and Nishinokaori, by 15-33 for Nebarigoshi and by 14-30 for Yumeshiho under late sowing. Nebarigoshi had a longer duration from sowing to flowering for Nov 8 and Nov 29 sowing, compared with the other three varieties, but the duration from flowering to maturity was shorter, and thus, the maturity dates were similar to the other varieties. For Oct 17 sowing the duration from sowing to flowering was the longest for Ayahikari followed by Yumeshiho and Nishinokaori. However the date of maturity was more or less similar for three varieties (only Ayahikari matured one day after other two). Nebarigoshi was not sown in Oct 17 due to seed unavailability. Duration from flowering to maturity was shorter under Dec 19 sowing for all varieties.

a.



b.

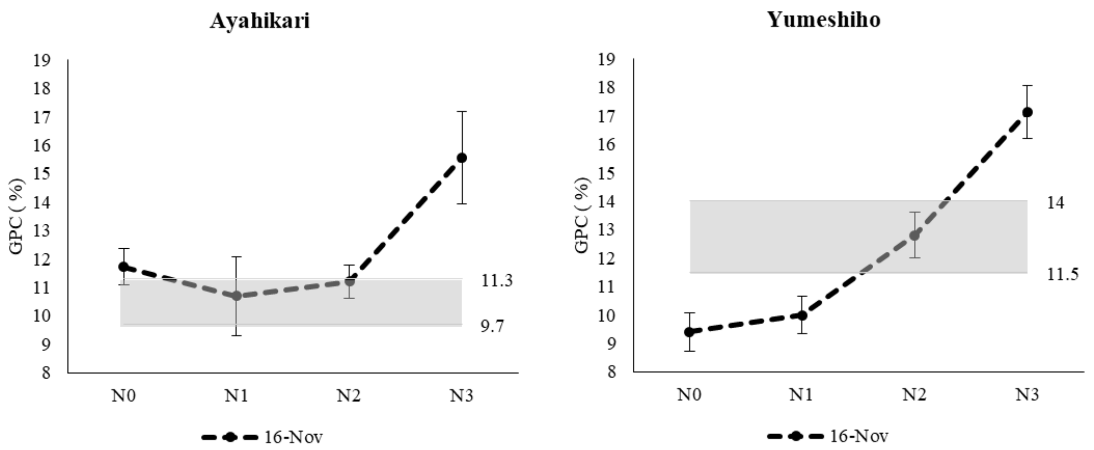


Figure 2.2 GPC response of the soft wheat variety (Ayahikari) and the hard wheat variety (Yumeshiho) to different N treatments at different sowing times (a: 2010–2011 and b: 2011–2012 experiments). Different lines represent different sowing dates. N treatments are N0, N1, N2, and N3 (0-0-0, 60-20-0, 60-20-30, and 60-20-60 respectively). Shaded areas show the rank A quality bonus window for GPC (hard wheat: 11.5–14%; soft wheat: 9.7–11.3%).

Variety	Sowing date	Date of flowering	Date of maturity	Duration (days): Sowing to flowering	Duration (days): Flowering to maturity	Duration (days): Sowing to maturity
Ayahikari	17-Oct	21-Apr	3-Jun	186	43	229
	08-Nov	3-May	12-Jun	176	40	216
	29-Nov	8-May	18-Jun	160	41	201
	19-Dec	13-May	18-Jun	145	36	181
Nebarigoshi	17-Oct					
	08-Nov	5-May	12-Jun	178	38	216
	29-Nov	11-May	18-Jun	163	38	201
	19-Dec	13-May	18-Jun	145	36	181
Yumeshiho	17-Oct	20-Apr	2-Jun	185	43	228
	08-Nov	2-May	12-Jun	175	41	216
	29-Nov	9-May	18-Jun	161	40	201
	19-Dec	13-May	18-Jun	145	36	181
Nishinokaori	17-Oct	17-Apr	2-Jun	182	46	228
	08-Nov	2-May	12-Jun	176	40	216
	29-Nov	9-May	18-Jun	161	40	201
	19-Dec	13-May	18-Jun	145	36	181

Figure 2.3 Effect of the sowing time on the date of flowering and physiological maturity, and the duration between sowing, flowering time, and physiological maturity for different wheat varieties

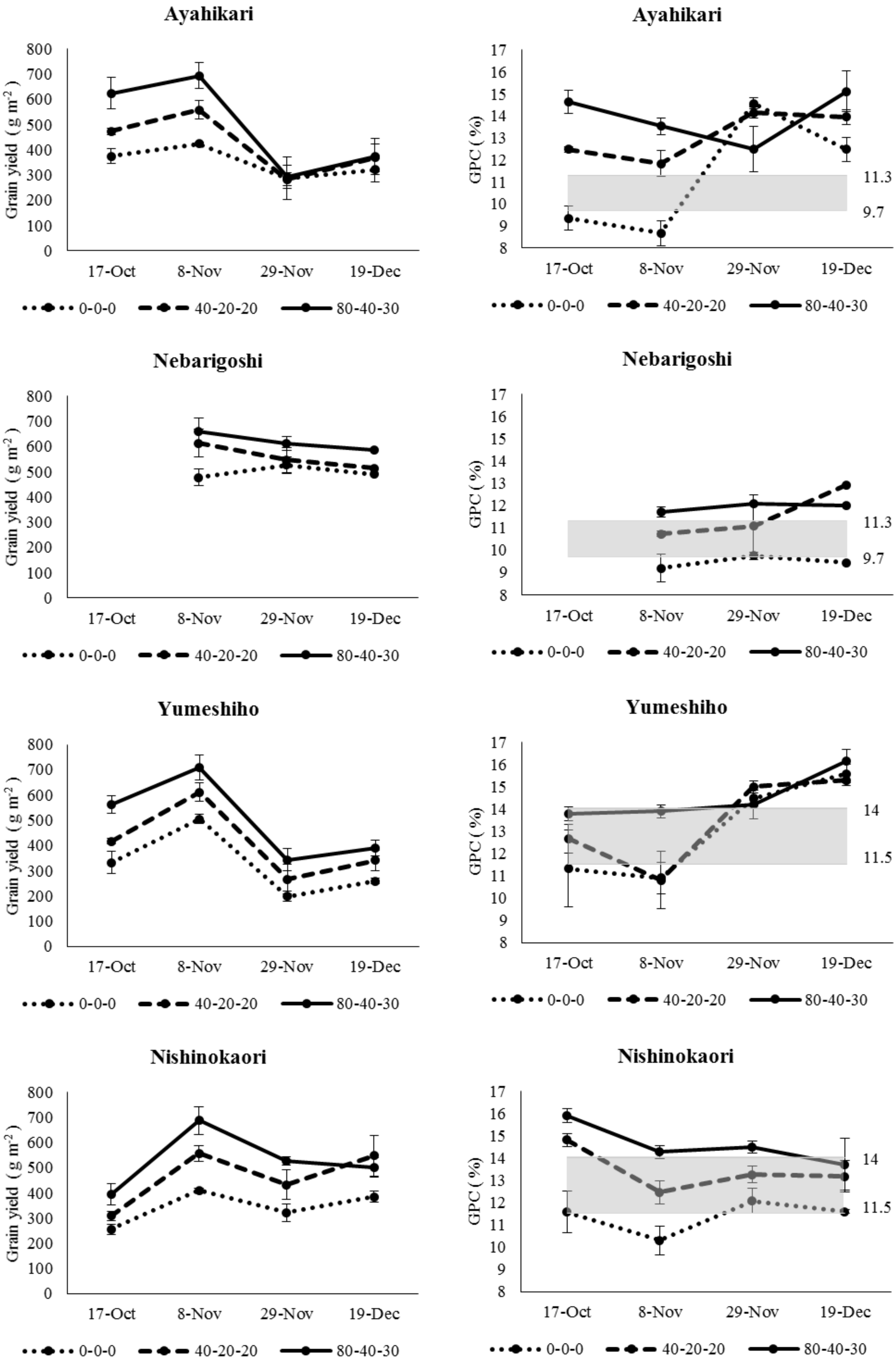

Ayahikari
Grain yield (g m^{-2})
800
700
600
500
400
300
200
100
0
17-Oct
8-Nov
29-Nov
19-Dec
0-0-0
40-20-20
80-40-30
Ayahikari
GPC (%)
17
16
15
14
13
12
11
10
9
8
11.3
9.7
Nebarigoshi
Nebarigoshi
Yumeshiho
Yumeshiho
14
11.5
Nishinokaori
Nishinokaori

Figure 2.4 Grain yield and GPC response of the soft wheat varieties (Ayahikari and Nebarigoshi), and the hard wheat varieties (Yumeshiho and Nishinokaori) to different N treatments at different sowing times (2012–2013 experiment). Different lines represent different N application rates (0-0-0, 40-20-20, and 80-40-30). Shaded areas show the rank A quality bonus window for GPC (hard wheat: 11.5–14%; soft wheat: 9.7–11.3%). No data for Nebarigoshi in the Oct 17 sowing group.

Table 2.4 Effect of N application rate (split), variety, and sowing time on the dry matter production at flowering and maturity, and the LAI in 2012–2013

	Dry matter at flowering (g m^{-2})		Dry matter at maturity (g m^{-2})		LAI	
Sowing						
17-Oct	860.3	b	821.8	a	2.29	a
8-Nov	1062.5	a	869.2	a	2.31	a
29-Nov	678.6	c	517.4	b	1.27	b
19-Dec	740.9	bc	557.7	b	0.88	b
Variety						
Ayahikari	674.7	b	639.5	a	1.43	a
Yumeshiho	754.7	b	630.2	a	1.51	a
Nebarigoshi	915.1	a	762.1	a	1.64	a
Nishinokaori	1010.8	a	719.3	a	2	a
Fertilizer						
0/0/0	726.6	b	594.6	b	1.35	b
40/20/20	871.3	a	684.7	ab	1.76	a
80/40/30	903.3	a	769.2	a	1.84	a
ANOVA						
Sowing (A)	***		**		**	
Variety (B)	***		***		***	
Fertilizer (C)	***		***		***	
A x B	***		***		***	
A x C	NA		NA		**	
B x C	NA		NA		NA	
A x B x C	NA		NA		NA	

Values are expressed on a dry matter basis

Same letters do not differ significantly (P<0.05, Tukey's test)

***,**,* : significant at P < 0.001, P < 0.01 and P < 0.05

Table 2.5 Effect of N application rate (split), variety, and sowing time on the grain yield, GPC, and yield components in 2012–2013

	Grain yield (g m^{-2})		GPC (%)		HI		Number of heads (m^{-2})		Number of grains ($head^{-1}$)		One thousand grain weight (g)	
Sowing												
17-Oct	363.4	b	14.8	a	0.46	c	457.8	a	20.8	b	38	a
8-Nov	503.4	a	12.9	b	0.58	b	465.1	a	31.6	a	34.7	b
29-Nov	337.7	b	15.1	a	0.66	a	363.8	b	32.2	a	33.1	b
19-Dec	369.9	b	15.5	a	0.67	a	394.5	b	29	a	33.2	b
Variety												
Ayahikari	369.6	b	14.7	a	0.61	a	351.2	b	31.8	a	36.8	a
Nebarigoshi	488.1	a	12.7	b	0.65	a	500.6	a	32.5	a	30.8	c
Nishinokaori	388.1	b	15.1	a	0.54	b	449.1	ab	24.1	b	36.9	a
Yumeshiho	359.6	b	15.4	a	0.61	a	391.2	b	28.3	ab	32.7	b
Fertilizer												
0/0/0	324.6	c	13.2	c	0.58	a	377.6	b	28.1	a	34.2	a
40/20/20	398.6	b	14.7	b	0.61	a	433.4	ab	27.3	a	34.8	a
80/40/30	463.6	a	15.9	a	0.62	a	442.5	a	31.4	a	34.7	a
ANOVA												
Sowing (A)	**		**		**		***		**		***	
Variety (B)	***		***		***		***		***		**	
Fertilizer (C)	***		***		*		NS		***		**	
A x B	***		***		NS		***		***		NS	
A x C	**		***		NS		NS		NS		NS	
B x C	NS		*		NS		NS		NS		NS	
A x B x C	NS		*		NS		NS		NS		NS	

Values are expressed on dry matter basis

Same letters do not differ significantly (P<0.05, Tukey's test)

***,**,* : significant at P < 0.001, P < 0.01 and P < 0.05

(2) Dry matter production

The statistical analyses indicated that the effects of sowing time, variety, and N application were significant for the total dry weight at flowering and maturity, as well as the leaf area index (LAI) at flowering (Table 2.4). These growth indices were highest for Nov 8 sowing, slightly tended to be lower for early sowing (Oct 17), and were significantly reduced for late sowings. Late sowing particularly affected the LAI. The sowing × variety interaction had a significant effect on all the growth indices ($P<0.001$), but the effect of sowing × fertilizer interaction was significant only for LAI ($P<0.01$) (Table 2.4).

(3) Grain yield and yield components

Application of 80 and 150 kg N ha^{-1} split at sowing, stem elongation, and flowering increased both the grain yield and the GPC significantly ($P<0.001$) (Table 2.5).

As for the yield components, the decreased grain yield under last sowing correlated well with the reduction in number of heads (Table 2.5). The harvest index was rather high for late sowing. With respect to the cultivars, the harvest index was lower for Nishinokaori (bread wheat cultivar) than for the other three cultivars. Again, the higher yield of Nebarigoshi and Nishinokaori was well reflected in the number of heads per area. The significant effect of increased N fertilizer rate on grain yield was highly correlated with the number of heads per area. The harvest index was also slightly increased by the N fertilizer application, although the effect was not significant.

Figure 2.4 shows the effect of both sowing time and N application on the grain yield and GPC. There was a general tendency that the yield was highest under the optimum sowing conditions (Nov 8) but more or less declined in the late sowing conditions. The pattern was, however, different between Ayahikai-Yumeshiho group and Nebarigoshi-Nishinokaori group. Yield decline from optimum sowing to late sowing tended to be less for the latter group. The highest grain yield was observed for Yumeshiho (707 g m^{-2}) at Nov 8 sowing under the highest N application.

(4) Grain protein content (GPC)

In average the GPC was the lowest at optimum sowing (Nov 8) and significantly higher for both later and earlier sowing (Table 2.5). Nishinokaori and Yumeshiho, the hard wheat varieties, had a higher GPC than a soft variety Nebarigoshi, but GPC of another soft variety Ayahikari was not different from hard varieties in this experiment. The N fertilizer application also increased GPC significantly. The sowing time × variety and sowing time × fertilizer interactions were also highly significant ($P<0.001$).

As shown in Figure 2.4, we observed a tendency of increasing GPC under delayed sowing conditions in general. Figure 2.4 suggests that the GPC content of Ayahikari and Yumeshiho sown at optimum timing are amenable to be changed, to fit into the quality bonus window through fertilizer application, but not under late sowing conditions under which GPC exceeded the higher limit of the quality bonus, regardless of the N application rate. Nebarigoshi and Nishinokaori, however, was suggested to produce GPC values within the quality bonus window even under the late-sowing conditions.

2.4 Discussions

2.4.1. The optimal sowing time was confirmed to be early-to-mid November

The yield results of the two experiments (Exp. 1 and 2; Tables 2.3 and 2.5, respectively) suggested that the optimal sowing window for wheat in Kanto region, Japan, is early-to-mid November, which is consistent with the prevalent practice in the region. Yield was significantly lower under earlier or later sowing conditions than under this optimal sowing conditions. As shown in Figure 2.1, the minimum temperature dropped to nearly zero in December in these three years, and therefore, plants sown before or during early-to-mid November could have an opportunity to produce enough fall tillers, which resulted in a higher grain yield. The yield component analysis in Exp. 2 showed significantly higher number of heads per area under the optimal sowing period (Table 2.5).

For the plants sown in the optimal period, better germination rates, good crop establishment (Farroq et al., 2008), and longer vegetative period can be expected, together with a better root growth, compared with the late-sowing conditions (Barraclough & Leigh, 1984). Thiry et al. (2002) reported that optimal-period sowing enhanced tillering during the fall, which is important for the final grain yield. In the experiment two, number of grains per heads and one thousand grain weight significantly reduced under early sowing (Oct 17) and thereby grain yield reduced compared to the optimal sowing (Table 2.5). Thiry et al. (2002) further reported that, very early planting produces excessive tillering during the fall, which leads to competition among tillers, causing a low percentage of formed spikes.

2.4.2. Delayed sowing decreased the grain yield but increased the GPC

We observed an increase in the GPC but decrease in grain yield under delayed sowing as general pattern (Figure 2.4). It was also reported previously that late sowing increases the GPC but reduces the grain yield but in soils other than the volcanic ash soils [e.g., Endoquolls and Eutrocryepts soils (Subedi et al., 2007)] and reduces the one thousand grain weight (Saleem et al., 2015). Barbottin et al. (2005) reported that nitrogen remobilized at maturity was highly positively correlated to nitrogen uptake at flowering. Therefore, when the carbohydrate translocation is limited as a result of poor vegetative growth under late sowing, N concentration in the grain increases due to the condensation effect. The significant interaction between the sowing time and fertilizer application rate, and between sowing time and cultivar in 2012–2013 season suggested that the effect of sowing time on grain yield and GPC is dependent on the cultivar and fertilizer application (Table 2.5).

2.4.3 The N application at flowering time to control GPC is effective only for optimal sowing

In this study, we observed the tendency that N application "at flowering" increased the GPC, but did not increase the grain yield significantly, in both hard and soft wheat grown in volcanic ash soils (Table 2.3). As reported in literature most grain N comes from the pre-anthesis assimilated N (Ehdaie & Waines., 2001), and N uptake continues during the grain-filling period (Asseng et al., 2002). Therefore, N application at flowering provides more N to the grain. Whereas, there is no more new leaf growth in the plant after flowering time (Hay and Porter, 2006) and it is only accumulated dry matter that translocated to the grain during the grain filling. Therefore N application at flowering may not add further benefit for increasing grain yield. On the other hand, the N application at stem elongation tended to increase the grain yield (Table 2.3). Stem elongation stage is important in establishing grain yield components, and therefore, providing N during this stage is effective in increasing grain yield (Kirby, 1998; Hay & Porter, 2006). The similar results have been reported elsewhere for the optimal-period sowing conditions (Nakano & Morita, 2009; Woolfolk et al., 2002; Fischer et al., 1993). The results of Table 2.3 are further explained by Figure 2.5, showing that grain yield increase was higher than GPC increase when N applied at stem elongation whereas GPC increase was higher than grain yield increase when further N applied at flowering time.

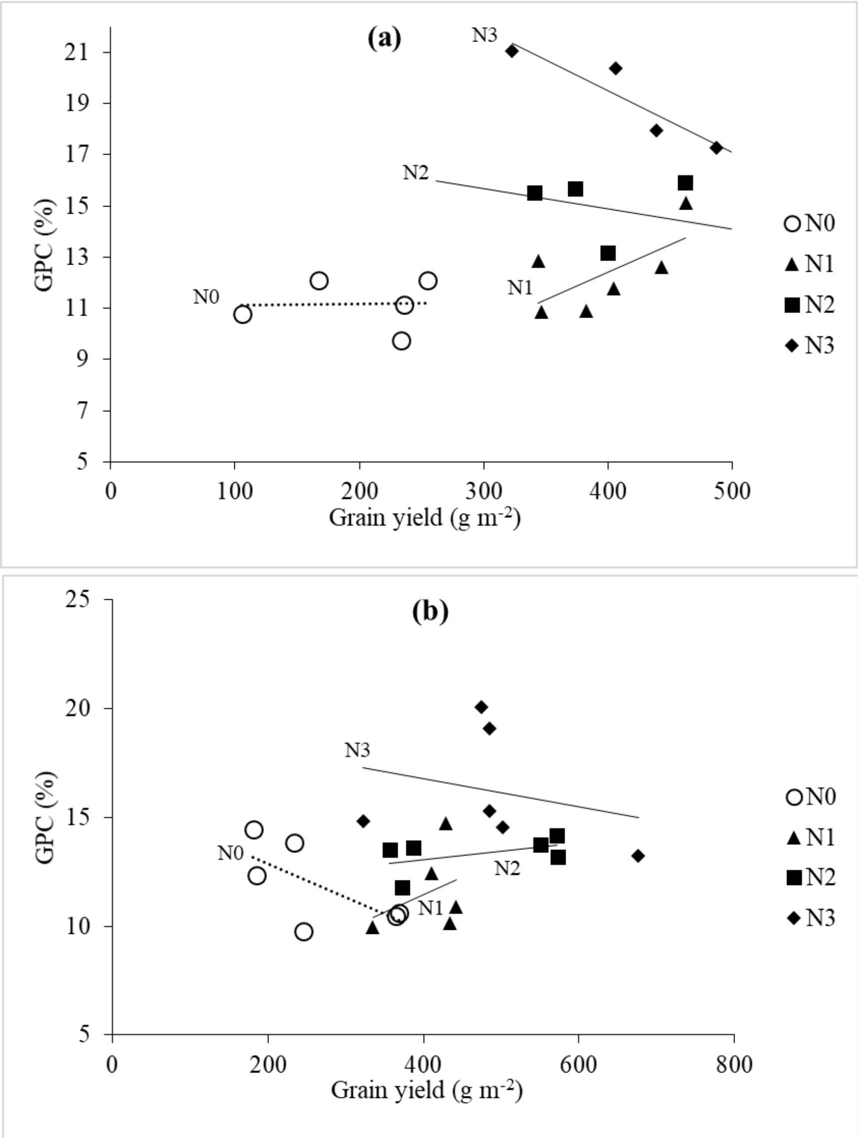


Figure 2.5 Grain yield-protein relationship for different N treatments; N0: 0-0-0, N1: 60-20-0, N2: 60-20-30, N3: 60-20-60 (2010–2011 Nov 2 sowing and 2011–2012 experiments). a: Yumeshiho (hard wheat), and b: Ayahikari (soft wheat). Each data point represents a replicate.

It has been proposed that N application at flowering can be used as a management option to adjust the GPC into the quality bonus window. My results demonstrated that the application of N at flowering to increase GPC was effective only for optimal-period sowing but not for late sowing, because the GPC of Kanto varieties (Ayahikari and Yumeshiho) under late sowing already exceeded the upper limit, even without N application (Figures 2.2 and 2.4). To my knowledge, this is the first report, discussing the effectiveness of flowering time N application in late-sowing conditions.

One of the major constraints for wheat cultivation in Kanto region, Japan, is the autumn rain, which delays the land preparation and machine sowing using drill planter. For example, wheat sowing was delayed in Gunma prefecture in 2016 due to the rains (Gunma Prefectural Government, 2017). This delayed sowing causes dual economic loss to the farmers: the lower yield and GPC surpass the quality bonus window. The present results suggest little or no N application at the time of flowering but at the stem elongation as the reasonable N-management strategy if the sowing is delayed.

2.4.4 Soil factors in the context of quantity of N to be applied at flowering time

According to the results, GPC of both hard and soft wheat grown in volcanic ash soils had a tendency to surpass the quality bonus window with N application at flowering. When N application at flowering time was increased from 30 to 60 kg N ha^{-1}, together with high total fertilizer application before anthesis (60 and 20 kg N ha^{-1} at sowing and at stem elongation, respectively), the GPC increased up to 15.6 and 17.1% in soft and hard wheat, respectively (Table 2.3). However, according to the Nakano et al. (2008), the increase of N application at flowering time from 30 to 60 kg N ha^{-1} (90 kg N ha^{-1} applied in total at sowing and tillering), the GPC of hard wheat increased only to the maximum of ca. 14.5% in Gray lowland soil. Shimazaki et al. (2015) also reported that, in volcanic ash soils, the original GPC content is higher than in Alluvial soils. These differences in GPC is suggested to be caused by the soil types different in the indigenous soil N supply. Eneji et al. (2002) reported that the native nitrogen supply capacity in volcanic ash soils is higher than that in other soils, and is further enhanced by the application of N fertilizers, which simulates the mineralization of the native soil nitrogen. The indigenous N content of Gray lowland soil is, reported to be lower than that of volcanic ash soils (Endo et al., 2013).

In 2011–2012, the GPC increased to a higher level (17.1%) compared with the other years (Table 2.3). The precipitation in early spring (March), when the maximum temperature starts increasing rapidly, was higher in 2012 compared with the other years, and it might have enhanced the soil N supply through mineralization. These results suggested that attaining the expected GPC in par with quality bonus standards, while increasing the grain yield, is difficult. The general fertilizer recommendations based on the results of field experiments may not merit unless the temporal variability of indigenous soil N supply is assured.

The plant growth and grain yield were relatively higher even under no nitrogen conditions in 2010-2011 season due to the fallowing period which preceded this experiment. The soil inorganic N content of the surface soil was in fact higher at the beginning of the experiment with no N application but it decreased after the two years of the cultivation.

2.4.5 Efficacy of N application at flowering time is different between hard and soft wheat varieties

The results showed that the effect of N application at flowering time was different between hard and soft wheat varieties. The GPC content of hard wheat tended to fit into the quality bonus window, whereas that of soft wheat surpassed it, in response to the flowering time N application (Figure 2.2). In Exp. 2 as well, it was found that 80, 40, and 30 kg N ha^{-1} at sowing, stem elongation, and flowering, respectively, resulted in the best N management for the hard wheat, Yumeshiho, for attaining a high grain yield (7 t ha^{-1}) and the standard GPC (Figure 2.4). Yumeshiho is a newly developed bread wheat cultivar, and therefore, my results confirmed its better performance as a bread wheat cultivar in the volcanic ash soils in Kanto region, Japan. On the other hand, the soft wheat (noodle) cultivar, Ayahikari, had a higher grain yield under optimal and early sowing with the same N-management strategy; however, it resulted in too high GPC values, surpassing the standards (Figure 2.4).

2.4.6 Adoption of cultivars from other regions that perform well under late-sowing conditions

Nebarigoshi (soft wheat) and Nishinokaori (hard wheat) are the recommended cultivars for Tohoku and western regions in Japan, respectively. The yield of these cultivars was not as high as that of Yumeshiho and Ayahikari, the recommended cultivars for Kanto region, when sown at the optimum time of the year (Figure 2.4). However, these two varieties attained a higher yield than Yumeshiho and Ayahikari, and maintained their GPCs within the quality bonus window, under the late-sowing conditions. The higher grain yield of Nebarigoshi and Nishinokaori under late sowing may be attributed to the higher number of heads per area. These results suggest the possibility of using Nebarigoshi and Nishinokaori under late-sowing conditions in the Kanto region, although further investigation is needed to confirm the applicability of this strategy by evaluating the reasons for better performance of Nebarigoshi and Nishinokaori under late sowing.

2.5 Conclusions

This study contributes to fill the information gap in the previous reports, regarding the interactive effects of split N fertilizer application at flowering stage and sowing time on the grain yield and GPC of both hard and soft wheat grown in volcanic ash soils.

The results suggested that N application at the flowering time for increasing the GPC is more suitable under optimum sowing conditions, where the GPC content of both hard and soft wheats can be adjusted to fit into the quality bonus window. Although early-to-mid November is the best time for sowing wheat in Kanto region, Japan, late sowing was also suggested to be possible with the right choice of cultivar and a proper N management strategy.

Chapter 3

Effects of late sowing on yield, yield components and seed emergence at low temperature for winter wheat in Kanto area

3.1 Introduction

The previous chapter demonstrated that the late sowing reduced the grain yield, and thereby GPC tended to increase for both hard and soft wheat of autumn sowing. The reduction of the grain yield was mainly caused by the reduction in number of heads per area. The number of heads per area can be further divided into the number of plants per area and the number of heads per plant. These traits can be affected by various physiological processes such as germination, emergence and plant survival during winter period under the low temperature, but the actual cause has not been elucidated well so far.

Therefore, a field experiment was conducted with both hard and soft wheat to conduct detailed analysis on the plant emergence and the changes of plant number during the winter period for the late sowing conditions in comparison to that for the optimal-time sowing conditions.

3.2 Materials and Methods

3.2.1 Experimental site

A field experiment was conducted at the Institute for Sustainable Agro-Ecosystem Services (ISAS), University of Tokyo at Nishitokyo City, Tokyo. The details of this site are described elsewhere in this thesis (2.2.1). The weather data (maximum and minimum daily temperature, precipitation and solar radiation) were obtained from the data recorded at ISAS.

3.2.2 Plant materials

Two recommended wheat varieties for Kanto region, Ayahikari and Yumeshiho were used. See the details in Chapter 2 (2.2.2).

3.2.3 Experimental procedures

The experiment was conducted for two seasons from November 2014 to June 2016.

3.2.3.1 Experimental design and treatments

The experimental design was split-split-plot with four sowing dates as the main factor, two wheat varieties (Ayahikari and Yumeshiho) as a subfactor, and two levels of N application (0 (N0), and 160 kg N ha^{-1} (N160)) as a sub-subfactor with three replications. The sowing dates were Nov. 14, Nov. 28, Dec. 10 and Dec. 24 in 2014, and Oct. 23, Nov. 13, Dec. 4 and Dec. 22 in 2015.

3.2.3.2 Crop management

N application for N160 treatment was split into two stages, i.e., at basal and at the stem elongation stage at 120 and 40 kg N ha^{-1}, respectively, as ammonium sulphate. Each plot area was 21 m^2. Phosphorus and potassium were applied as a single compound fertilizer (0:20:15:5=N:P_2O_5:K_2O:MgO) as basal application at a sufficient level (P_2O_5 100 kg ha^{-1} and K_2O 75 kg ha^{-1}). Sowing was conducted by a non-till drill seeder with 19 cm row spacing. The sowing density and depth were 80 kg ha^{-1} and 25 mm, respectively. The standard sowing window is early-to-mid November in the Kanto region (http://www.pref.chiba.lg.jp/annou/documents/3-2-3.pdf), and therefore, October sowing is considered as early sowing and late-November to December sowings are as late sowing.

3.2.3.3 Plant measurements

Crop phenology was recorded weekly using Zadoks scale (Zadoks et al., 1974). Seed germination was observed one week after the each sowing for both varieties. Around 10 seeds per plots were randomly collected by excavation with a scoop and their germination was confirmed visually in both N0 and N160 plots of replicate two.

Plant emergence was observed every week from sowing date to till March (March 11and 29 in 2015 and 2016 respectively) and the number of emerged plants were counted visually at the marked area of 1×0.57 m in N0 and N160 plots of replicate two. Emergence percentage was calculated based on the initial number of plants calculated from sowing density (assumed all seed sown germinated). Date of emergence was determined as the date of 50% emergence compared with the maximum emergence percentage by interpolating the weekly basis emergence percentage. Maximum emergence percentage was calculated as the average of emergence percentages after its increase ceased. At the flowering stage plants in

0.50 × 0.57 m area of each plot was sampled for the analysis of leaf area index (LAI) and total biomass. Subsamples were taken from the main samples and plants were separated into green leaves, yellow and dead leaves, stems (including leaf sheath) and spikes. Leaf area was measured for the green leaf samples using area meter (Li-Cor LI-3100C, Lincoln, USA). All samples were dried at 80 °C in a forced air oven for 72 hours to obtain the dry weights.

At physiological maturity, the plants in 1 m × 0.95 m area of each plot were sampled for the analysis of grain yield, total biomass, and harvest index. The dry matter and grain dry weight were determined by drying the samples at 80 °C until constant weights were achieved. The grain N content was analyzed by the dry combustion method (Elemental Analyzer Flash EA 112, Thermo Electron Corporation, Delft), and the conversion factor of 5.7 was used to derive the GPC from N content. At the sample time of physiological maturity, ten heads of sample within each plot were collected randomly from N160 plots from each sowing groups (both varieties) to calculate the number of grains per gram stem. Calculated grains per gram stem data was used for the APSIM model calibration described in chapter 4.

Recommended herbicides were applied three weeks before the sowing and once during the growing period. Weeds were removed manually when it is necessary. No pesticide or fungicide was applied but the plots were relatively clean throughout the growing seasons.

3.2.3.4 Soil measurements

Soil samples were monthly collected from the plots of first sowing group of Yumeshiho at 0-20 cm depths from March to June for two seasons. Soil samples were air-dried and passed through 2 mm sieve. Nitrate nitrogen (NO_3^--N) were extracted with 20 mL of distilled water using 5g of air-dried soil, and their concentration was measured with a combination ion-selective electrode for nitrate (9707BNWP Thermo Fisher Scientific, Waltham, USA). These data of soil NO_3-N was used for the APSIM model validation described in Chapter 4. Soil temperature at 5 cm depth was measured from December 2014 to February 2015 by installing a temperature sensor (ECH2O 5TE Sensor, Meter Group, Inc. USA) connected to a data logger in the plot of 160 kg N treatment, Yumeshiho of Nov 28 sowing group, replicate two.

3.2.3.5 Analysis on the effect of temperature on plant emergence

Analysis was conducted between average air temperature (during the period from the date of sowing to the date of emergence) and number of days taken from sowing to the date of emergence. Average temperature from sowing to the date of emergence was calculated as a grand average of the daily average of maximum and minimum temperature of the respective period. Based on Milthorpe and Moorby (1979) and Addae and Pearson (1992), the relationship between emergence percentage and rate of emergence (reciprocal of the number of days to the date of emergence) was also analysed.

3.2.4 Statistical analysis

Analysis of variance was (ANOVA) was used to test the effects of year, sowing time, variety, fertilizer treatment and their interactions on grain yield, yield components, GPC, dry weight at maturity with R statistical software 3.2 (R Development Core Team 2008). To identify the significant differences, the LSD was used when *F* test was significant ($P<0.05$). Correlation analysis between grain yield and each yield component was conducted with the same statistical software to elucidate the significant yield components that affected the grain yield under late sowing conditions.

3.3 Results

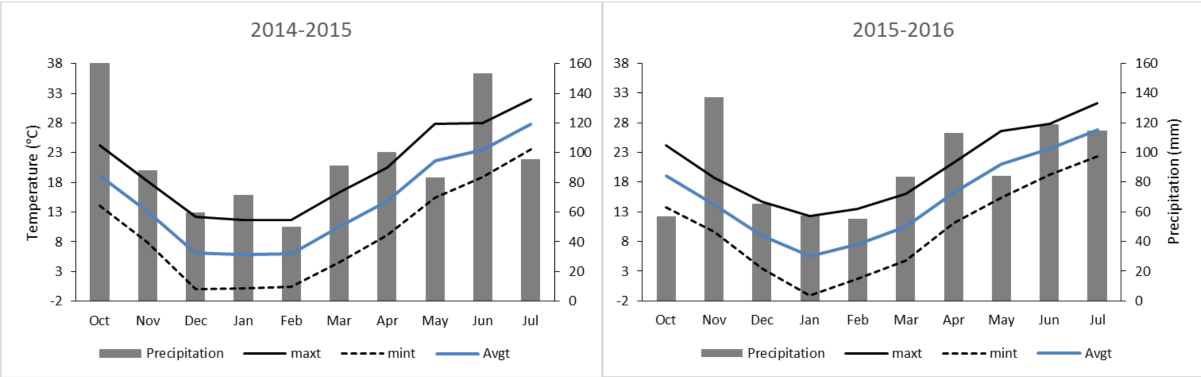
3.3.1 Weather conditions

Both seasons for the experiment had similar patterns for temperature and rainfall. However, October rainfall was much higher in 2014-2015 than in 2015-2016 (Figure 3.1 a). Minimum temperature in December and February was higher in 2015-2016 than in 2014-2015. Maximum temperature also followed the similar pattern as the minimum temperature. During the months of October to December, daily average air temperature did not drop less than 7 ºC in both seasons.

Daily minimum and maximum temperatures and their averages during the period from October to March are shown in Figure 3.1 b. Daily minimum air temperature dropped below 5 ºC once in mid November but recovered again in 2014-2015 season. From December to late February, the minimum temperature was almost consistently below 5 ºC. There were again two spikes of lower minimum temperature in mid and late March. In 2015-2016, such period when the daily minimum temperature was below 5 ºC continued from late November to early March followed with two colder short periods. Daily average air temperature only sporadically dropped below 5 ºC from mid December to mid-February in 2014-2015, and from mid-January to mid-February in 2015-2016.

The soil temperature at 5 cm depth seems to have followed the daily average air temperature with 1-2 days delay (Figure 3.1 c). Soil temperature was consistently lower than the air temperature from early to mid-January. There is a significant correlation between daily average air temperature and soil temperature at 5 cm depth for these measurement ($R^2 = 0.77$, $P < 0.001$).

a.


2014-2015
2015-2016
Temperature (°C)
Precipitation (mm)
Oct Nov Dec Jan Feb Mar Apr May Jun Jul
Precipitation
maxt
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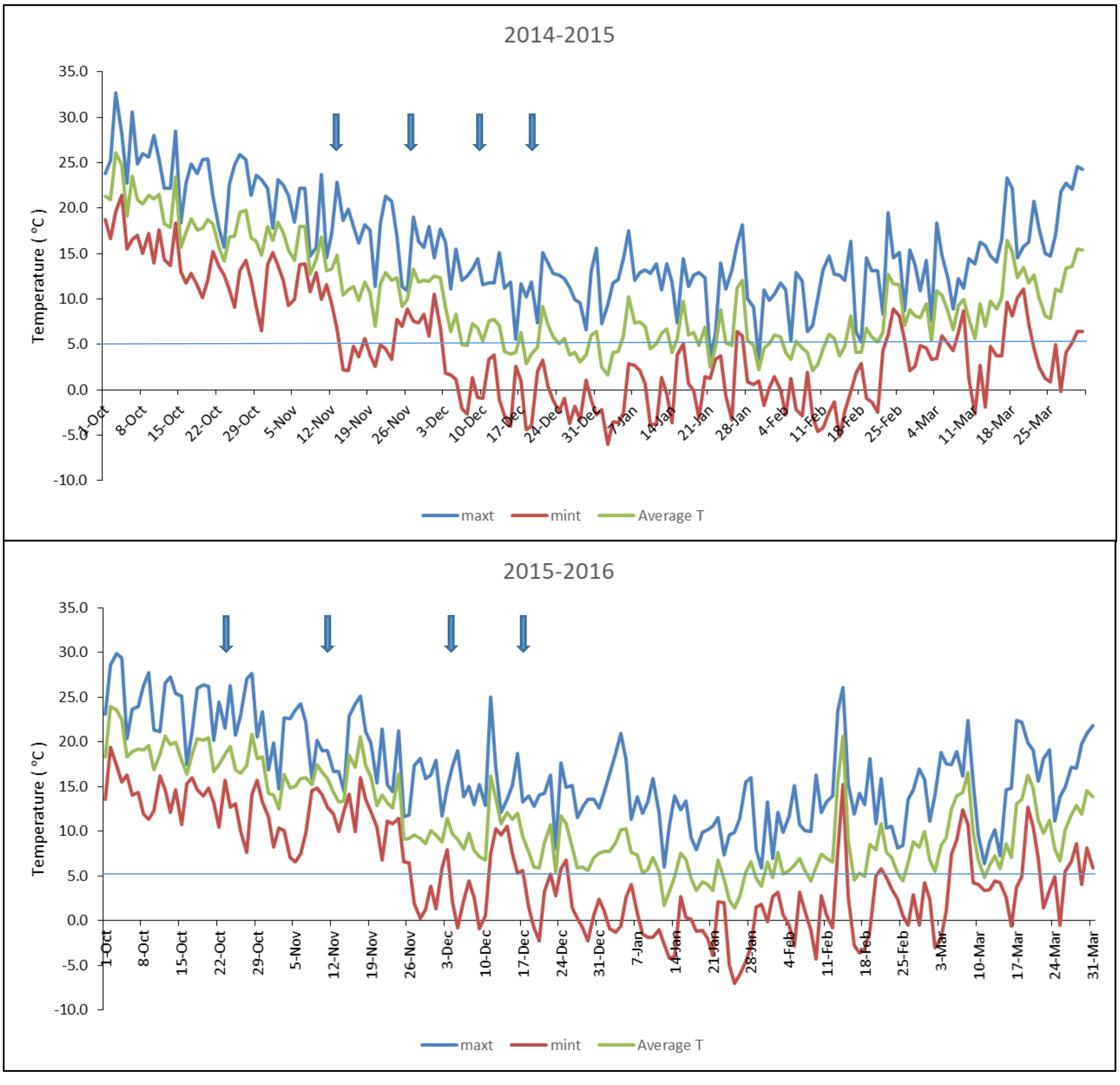
b.


2014-2015
2015-2016
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c.

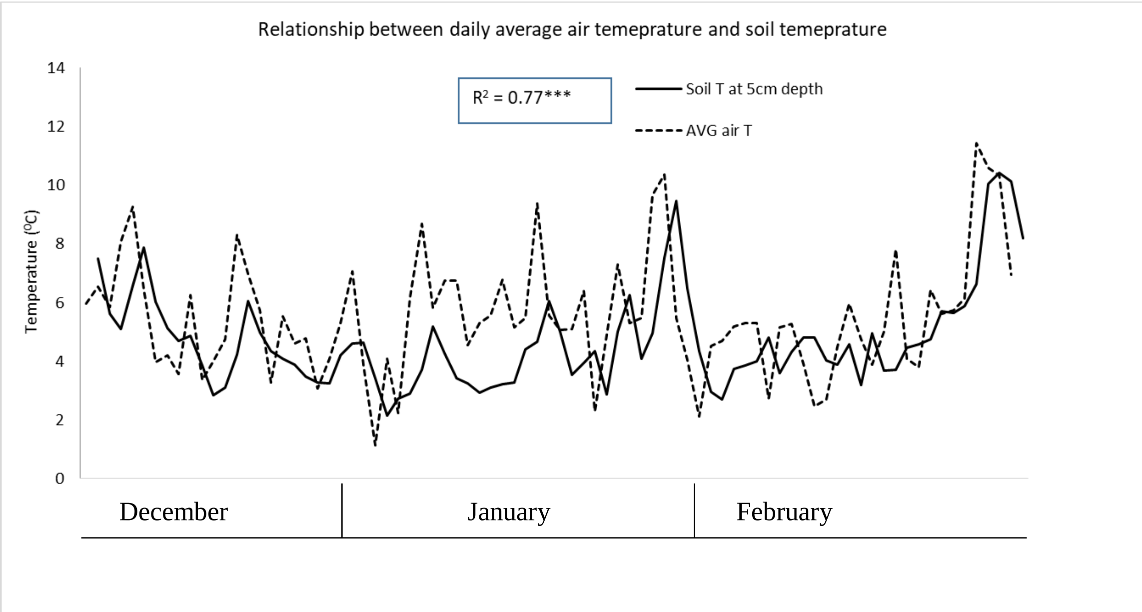


Figure 3.1 (a.) Monthly average of daily minimum, maximum and average temperatures and, monthly rainfall, in 2014-2015 and 2015-2016 cropping seasons. (b.) Changes in daily minimum, maximum and average temperatures from December to March in 2014-2015 and 2015-2016 (blue arrows denote sowing dates). (c.) Daily average air temperature and soil temperature at 5 cm depth from 2014 December to 2015 February.

3.3.2 Grain yield and yield components

Results of ANOVA for yield and yield related traits showed that grain yield was significantly affected by sowing date, fertilizer application rate and their interaction ($P<0.001$ for all effects) (Table 3.1). GPC was affected by sowing date ($P<0.01$), variety ($P<0.001$), fertilizer application rate ($P<0.001$), and by several interactions. Total dry weight was also affected by sowing date, fertilizer rate, and their interaction, plus interaction between year and fertilizer rate. Regarding the yield components, number of heads per area ($P<0.001$), number of grains per head ($P<0.05$) and one thousand grain weight ($P<0.01$) were significantly affected by sowing date.

As shown in Table 3.2, grain yield was significantly reduced under latest sowing conditions for both varieties in both seasons (except for N0 treatment in 2014-2015), compared to that of optimal sowing dates. On the contrary, GPC increased at late sowing conditions for both varieties in both seasons. Number of heads per area was also significantly reduced under late sowing conditions at N160 treatment.

The degree of grain yield reduction at later sowing conditions was similar to the reduction of number of heads per area but not to number of grains per head nor the thousand grain weight in both hard and soft wheat varieties in two seasons (Figure 3.2). The result of the correlation analysis among yield and yield components showed that grain yield was significantly correlated with number of heads per area ($r = 0.92$) and with number of grains per head ($r = 0.78$) but not with thousand grain weight (Table 3.3).

Table 3.1 Results of ANOVA for grain yield, GPC, dry matter production and yield components.

	Yield (g m^{-2}) (12.5% moisture)	GPC % (13.5% moisture)	Total dry weight (g m^{-2})	Number of heads per area (m^{-2})	Number of grains per heads	Thousand grain weight (g)	Harvest Index
ANOVA							
Year (A)	NS	NS	NS	NS	NS	NS	*
Sowing (B)	***	**	***	***	*	**	*
Variety (C)	NS	***	NS	**	NS	***	**
Fertilizer (D)	***	***	***	***	***	***	NS
A x C	NS	*	NS	NS	NS	NS	*
B x C	NS	NS	NS	NS	NS	NS	NS
A x D	NS	NS	*	NS	NS	*	NS
B x D	***	*	***	***	NS	*	*
C x D	NS	*	NS	NS	NS	NS	NS
A x C x D	NS	NS	NS	NS	NS	NS	NS
B x C x D	NS	NS	NS	NS	NS	NS	NS

***,**,* : Significant at P<0.001, P<0.01, and P<0.05

Table 3.2 Grain yield, GPC, dry matter production and yield components for Ayahikari (a.) and Yumeshiho (b.) in 2014-2015 and 2015-2016.

a.

Year	Sowing time	Fertilizer treatment	Yield (g m^{-2}) (12.5% moisture)	GPC % (13.5% moisture)	Total dry weight (g m^{-2})	Number of heads per area (m^{-2})	Number of grains per heads	Thousand grain weight (g)	Harvest Index
2014-2015	14-Nov	N0 (0 kg N ha-1)	200	10.9 ab	290	182 ab	25	39 a	0.61 b
	28-Nov		212	8.7 b	289	233 ab	23	35 b	0.65 a
	10-Dec		195	10.9 ab	278	161 b	31	36 b	0.62 ab
	24-Dec		155	12.5 a	231	174 ab	23	35 b	0.59 b
	14-Nov	N160 (160 kg N ha-1)	516 a	11.7 b	713 a	371 a	39 a	32	0.64
	28-Nov		465 a	12.2 b	661 a	298 ab	45 a	31	0.63
	10-Dec		452 a	12.9 ab	620 a	264 ab	49 a	30	0.64
	24-Dec		172 b	14.5 a	247 b	239 b	20 b	32	0.62
2015-2016	23-Oct	N0 (0 kg N ha-1)	161 a	8.8 c	265 bc	170 b	24	35 b	0.54 a
	13-Nov		192 a	8.9 c	341 a	221 a	21	38 a	0.50 b
	4-Dec		167 a	9.5 b	282 ab	171 b	25	35 b	0.52 ab
	22-Dec		99 b	12.5 a	204 c	159 b	18	30 c	0.43 c
	23-Oct	N160 (160 kg N ha-1)	538 a	10.9 c	998 a	375 b	37	35 a	0.48
	13-Nov		528 a	10.7 c	873 a	418 a	33	34 a	0.53
	4-Dec		295 b	12.1 b	501 b	290 c	31	30 b	0.52
	22-Dec		149 c	13.6 a	250 c	137 d	33	29 b	0.53

Same letters do not differ significantly (P<0.05, LSD test)

b.

Year	Sowing time	Fertilizer treatment	Yield (g m^{-2}) (12.5% moisture)	GPC % (13.5% moisture)	Total dry weight (g m^{-2})	Number of heads per area (m^{-2})	Number of grains per heads	Thousand grain weight (g)	Harvest Index
2014-2015	14-Nov	N0 (0 kg N ha-1)	219	12.5 ab	309	219	23	40 a	0.62
	28-Nov		221	9.5 b	309	224	28	32 ab	0.63
	10-Dec		179	14.4 ab	249	173	32	31 ab	0.64
	24-Dec		144	18.5 a	216	198	21	30 b	0.56
	14-Nov	N160 (160 kg N ha-1)	582 a	12.7 c	778 a	501 a	35	31 a	0.66 a
	28-Nov		387 b	12.9 c	545 b	300 b	38	30 a	0.63 ab
	10-Dec		373 b	13.9 b	533 b	331 b	35	29 ab	0.62 ab
	24-Dec		167 c	15.2 a	254 c	226 b	27	26 b	0.57 b
2015-2016	23-Oct	N0 (0 kg N ha-1)	120 ab	9.6 b	241 b	189	17 a	33 ab	0.43 ab
	13-Nov		184 a	10.2 b	335 a	188	25 ab	35 ab	0.48 ab
	4-Dec		176 ab	10.8 ab	316 ab	192	28 a	30 c	0.49 a
	22-Dec		111 b	12.1 a	239 b	151	20 ab	31 ab	0.39 b
	23-Oct	N160 (160 kg N ha-1)	395 ab	11.8 ab	819 a	386 ab	31	31	0.43
	13-Nov		463 a	11.7 ab	822 a	429 a	30	32	0.50
	4-Dec		316 b	11.3 b	539 b	316 b	30	29	0.52
	22-Dec		146 c	13.2 a	296 b	190 c	23	30	0.43

Same letters do not differ significantly ($P<0.05$, LSD test)

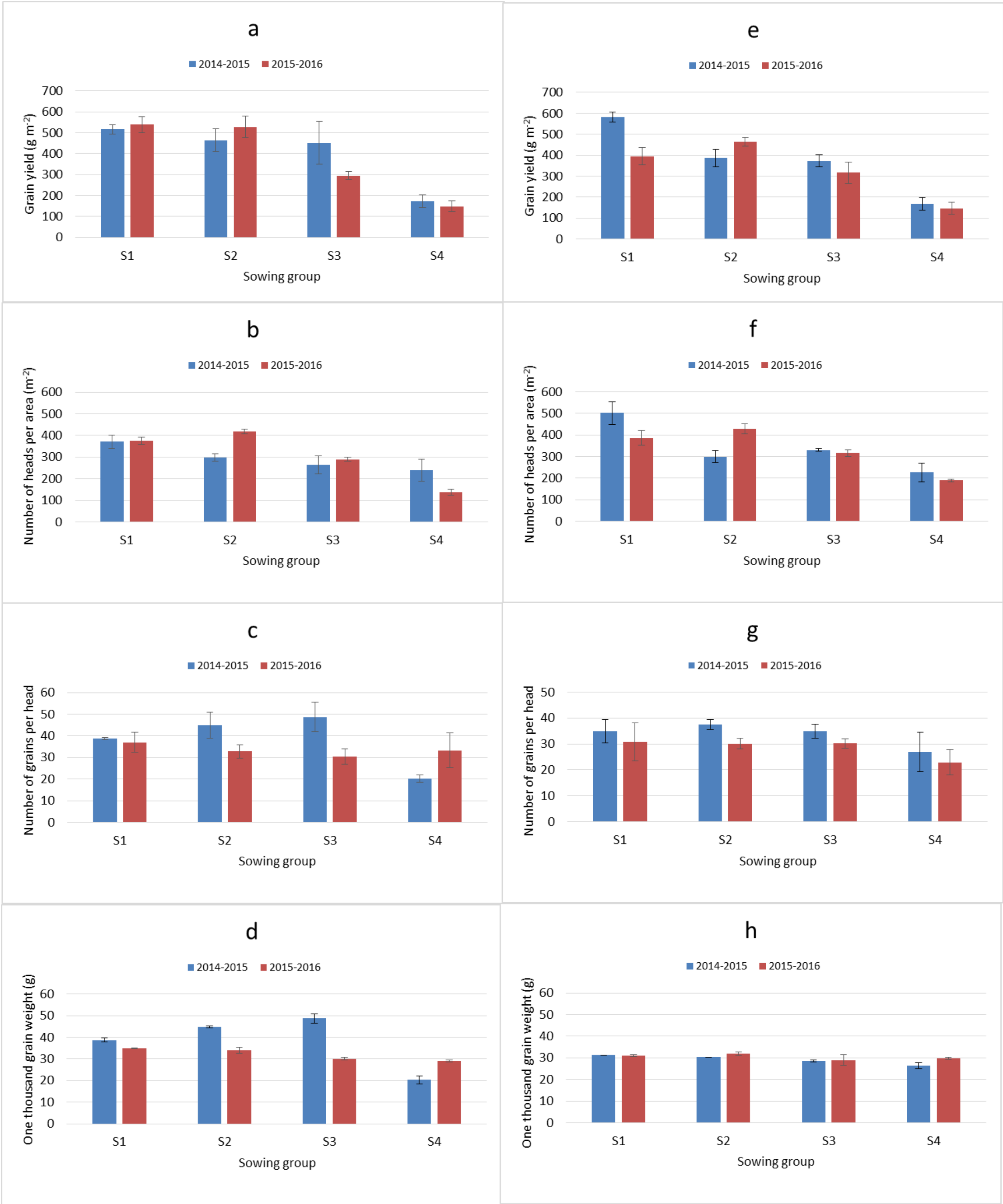


Figure 3.2 Grain yield and yield components under N160 treatment for Ayahikari (a-d) and Yumeshiho (e-f) in 2014-2015 and 2015-2016. S1, S2, S3 and S4 are Nov-14, Nov-28, Dec-10 and Dec-24 for 2014-2015 season and Oct-23, Nov-13, Dec-4 and Dec-22 for 2015-2016 season, respectively.

Table 3.3 Correlation coefficient among grain yield and yield components. The data of all N treatments for two varieties in two seasons were used for the analysis.

	Grain Yield	No of heads per area	Number of grains per head	Thouasnd grain weight
Grain Yield	1			
No of heads per area	0.92***	1		
Number of grains per head	0.78***	0.53	1	
Thouasnd grain weight	-0.08	-0.15	-0.27	1

***,**,* : Significant at P<0.001, P<0.01, and P<0.05

3.3.3 Plant emergence

The changes of the emergence percentage in 2014-2015 and 2015-2016 seasons are shown in Figures 3.3 and 3.4, respectively. The results indicated that number of days taken from sowing to emergence was more under late sowing conditions. In both cropping seasons, plants sown under optimum sowing period reached maximum emergence percentage in around two weeks whereas the plants sown under latest dates took almost two months to emerge. The maximum emergence percentage tended to have decreased under late sowing conditions compared to that under optimal sowing conditions (i.e., Nov 14 in 2014 and Nov 13 in 2015) for both hard and soft wheat varieties.

In general the air and soil temperatures decrease under the late sowing conditions for winter wheat sown in autumn. Therefore, as shown in Figure 3.5, the number of days to emergence increased when the average daily air temperature averaged during emergence period decreased. It seems that the number of the days from sowing to emergence started to increase when the average temperature decreased lower than 10 °C (Figure 3.5).

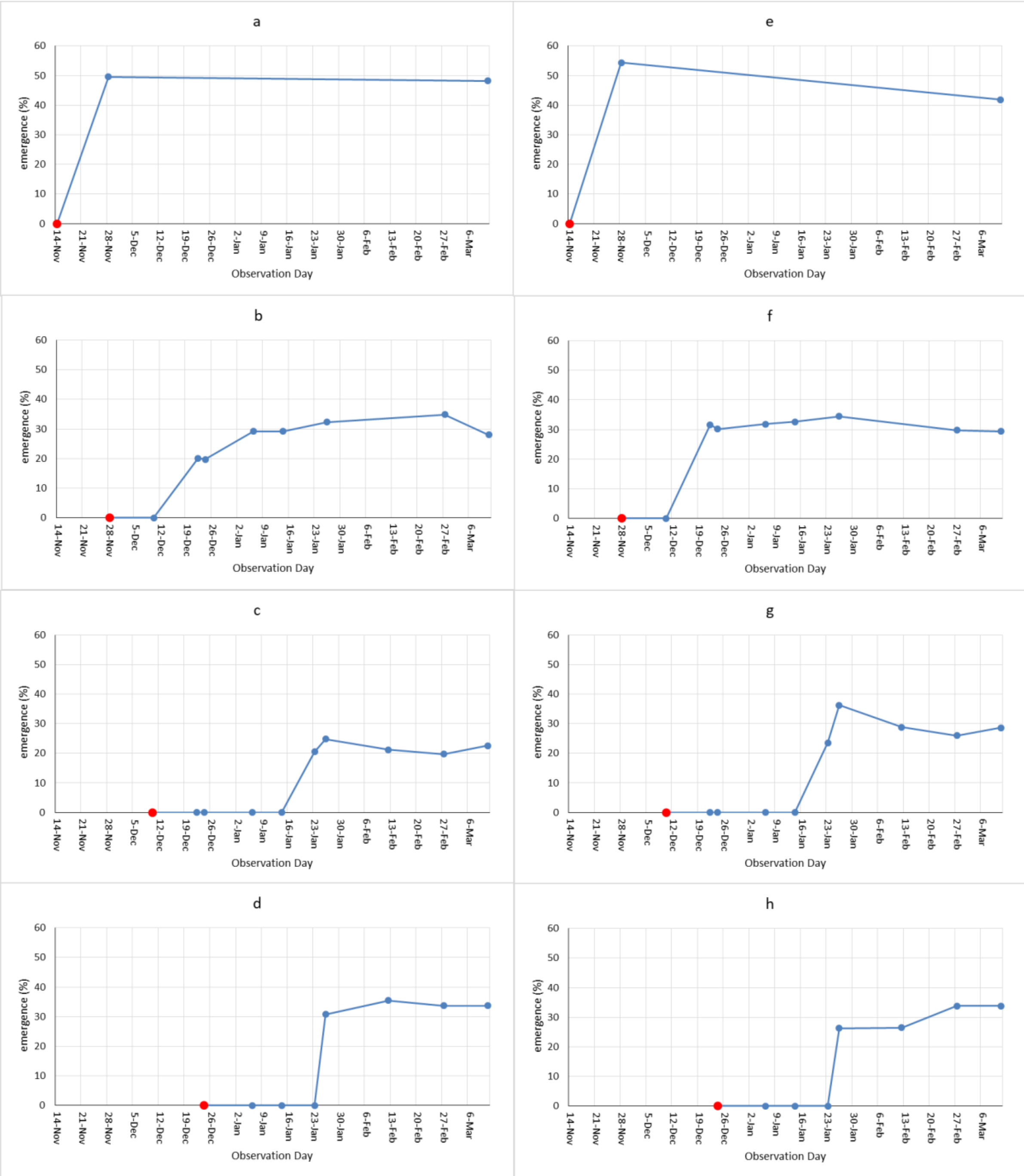


Figure 3.3 Changes of emergence percentage for Ayahikari (a-d) and Yumeshiho (e-h) in 2014-2015. Different sowing times denoted as; a and e: Nov-14, b and f: Nov-28, c and g: Dec-10, d and h: Dec-24. Red data points show the sowing dates.

Figure 3.4 Changes of emergence percentage for Ayahikari (i-l) and Yumeshiho (m-p) varieties in 2015-2016. Different sowing times denoted as; i and m: Oct-23, j and n: Nov-13, k and o: Dec-04, l and p: Dec-22. Red data points show the sowing dates.

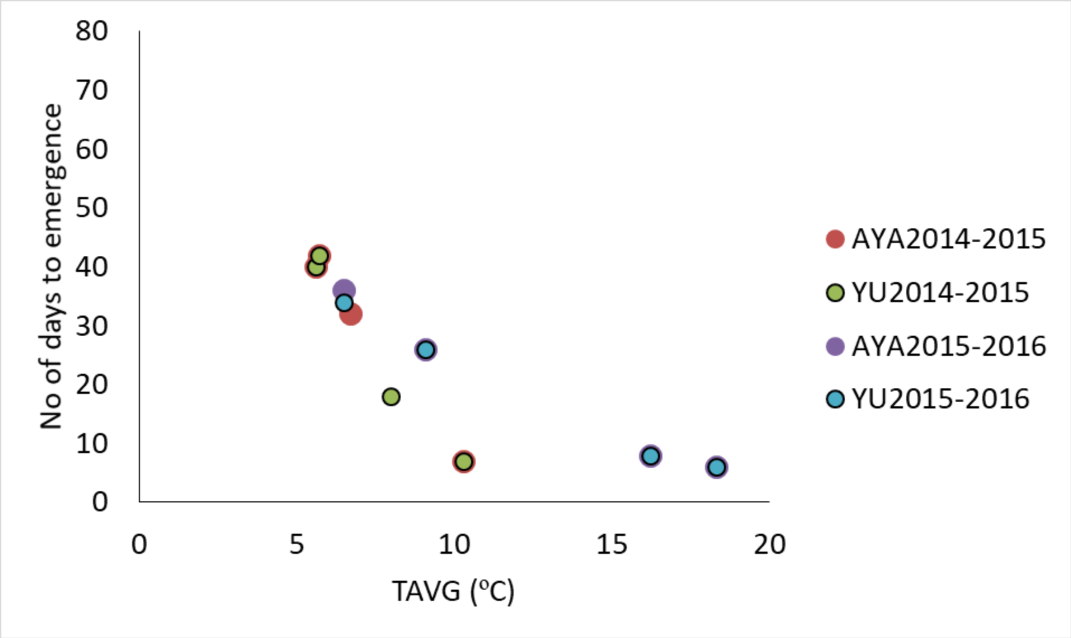


Figure 3.5 Relationship between number of days to emergence and average temperature during the emergence period (TAVG; ˚C) for Ayahikari and Yumeshiho varieties, in 2014-2015 and 2015-2016.

3.3.3.1 Germination, the number of plants both at maximum emergence and in March

According to the field observation of seed germination, germination per se generally completed within one week after the sowing for both varieties in all sowing dates including the late sowing conditions. The low soil/air temperature of the late sowing did not delay the germination ratio nor decrease the ultimate germination percentage. And therefore, number of plants per area (m^{-2}) at germination was assumed to be 206 and 249 in 2014, and 226 and 247 in 2015 for Yumeshiho and Ayahikari, respectively, which was calculated from the recorded amount of seeds dropped to the field during sowing operation and thousand grain weight of the seeds measured before the sowing. Figure 3.6 shows the expected plant number at germination calculated as above, observed plant number at maximum emergence and observed plant number in March, for latest sowing treatment in both years. The results showed that plant number was greatly reduced during the period between the completion of germination and at maximum emergence. The reduction was by 76 and 83 % for Dec. 24 sowing in 2014 and 82 and 71% for Dec. 22 sowing in 2015 for Ayahikari and Yumeshiho, respectively.

On the contrary, the decrease in number of plants during the period between maximum emergence and in March (which corresponded to the stem elongation stage for early sown plants but to the late tillering stage for late sown plants) was minimal. The reduction was 7 and 8% for Ayahikari in 2014 and 2015 respectively, and 8% for Yumeshiho in 2015. The number of plants, however, increased by 29% during this period for Yumeshiho for 2014 sowing.

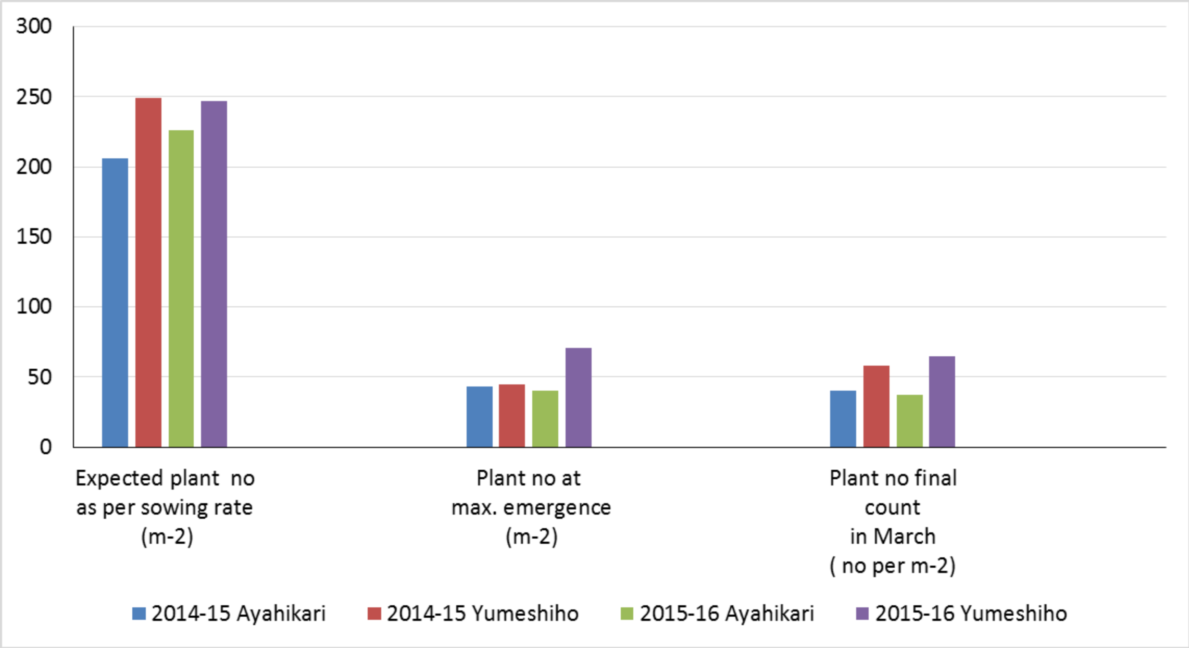


Figure 3.6 Expected number of plants at germination, the observed number of plants at maximum emergence and in March (m^{-2}) for Ayahikari and Yumeshiho (Dec 24 and Dec 22 latest sowing groups of 2014-15 and 2015-16 respectively).

3.3.3.2 Relationship between the number of days to emergence and the number of plants at maximum emergence

Figure 3.7 shows the relationship between maximum emergence percentage and the rate of emergence (reciplocal of the number of days from sowing to the date of emergence). A quadratic curve could fit relatively well with a high coeficient of determination (R^2 = 0.8296). The slopes (P<0.001, P<0.05) and intercept (P<0.05) were also significant. With this equation, the maximum percentage of emergence can be calculated from the number of days needed from sowing to emergence, for both Ayahikari and Yumeshioho varieties across the conditions of two seasons.

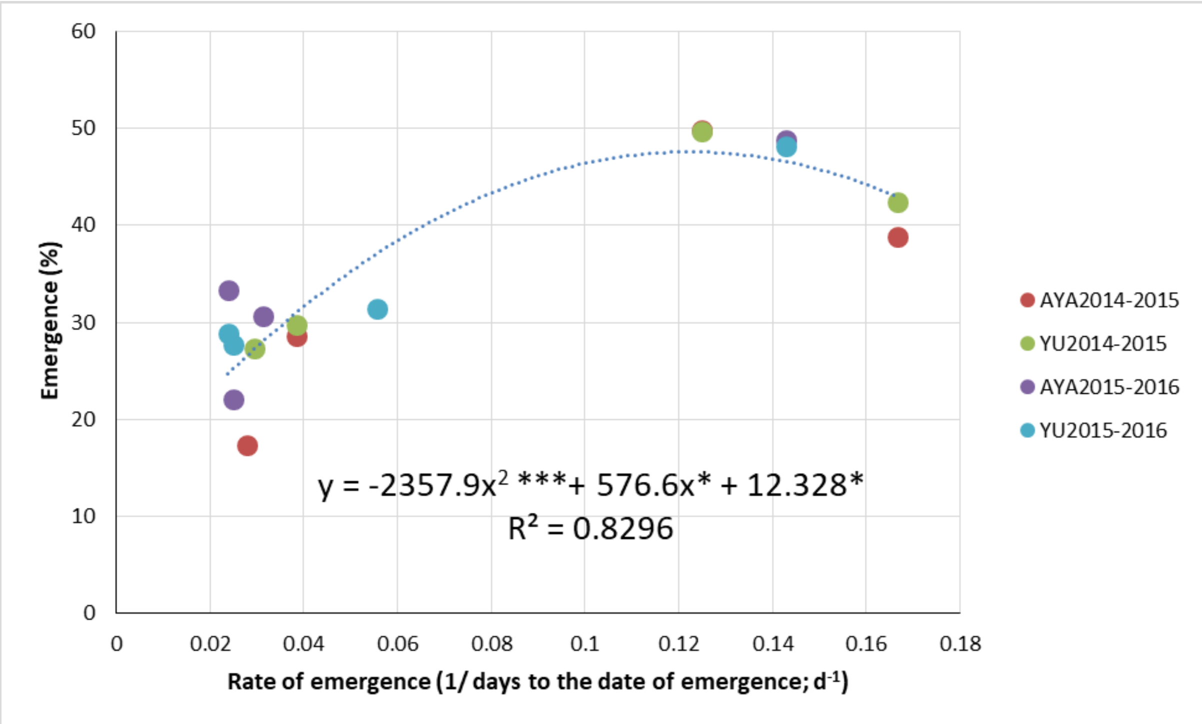


Figure 3.7 Relationship between maximum emergence percentage and rate of emergence (1/ number of days to the date of emergence). *,*: significant at P<0.001, P<0.05**

3.4 Discussion

The weather conditions of both seasons were the typical ones of the inland area of Kanto plane. The monthly precipitation was relatively higher in October or November due to the sporadic typhoon visits, and then it was relatively dry from December to February with around 50 mm of monthly precipitation. The precipitation increased slightly in March and April due to so-called “spring rain” of the region. And then it rained more in June and July due to the East Asian rainy season. The total precipitation from October to July was average (1148 mm) in 2014-2015 but less (887 mm) in 2015-2016, compared with that of the average of past 30 years (1981-2010) at Fuchu Meteorological Station (8 km away from the experimental site) (1116 mm). Although there was some fluctuation during the entire wheat growing period, the precipitation is not considered as the growth-limiting factor for these years.

The soil temperature at 5 cm depth should be close to the one which the sown seeds experienced. This soil temperature, in general, followed the daily average air temperature with 1-2 days delay and there was a good correlation between daily average air temperature and soil temperature at 5 cm depth ($R^2 = 0.77$, $P < 0.001$), although it did not increase as high as the air temperature when the latter increased (Figure 3.1 c). Since it is much easier to obtain the data of air temperature than the soil temperature in general, and therefore air temperature was used in this thesis to analyse the effect of low temperature on the germination and emergence of the sown seeds. This compromise would be accepted because the analytical results of the effect of low temperature on the wheat growth is meant to be used for the model analysis where the air temperature is the direct input data.

The results of the experiment for two seasons confirmed one of the main conclusions of Chapter 2 that the late sowing conditions reduced grain yield and increased GPC for both hard and soft wheat. Total dry weight, number of heads per area, number of grains per heads and, thousand grain weight also reduced under the late sowing conditions (Table 3.2). However, the main yield components which affected the grain yield was found to be the number of heads per area and number of grains per head (Table 3.3), and the former more explains the reduction in the late sowing conditions than the latter (Figure 3.2). Kelley (2001) and Tomar et al. (2014) also reported that number of heads per area was significantly reduced for wheat grown under late sowing conditions.

The number of heads per area can be further divided into the number of plants per area, and the number of heads per plant, i.e., degree of tillering. The field observation in March confirmed the lower degree of tillering in the late sowing treatment. But, since those plants were still in the tillering stage in March and the number of tillers were increasing while the plants in early sowing treatment were already in the stem elongation stage without further increase in the tiller number, it was assumed that the number of heads per plants was not so much different between late and early sowing treatments. However reduction in the number of plant population was evident from the data of maximum (ultimate) number of emergence (Figure 3.3 and 3.4). The aerial photo taken in March also showed that the poor plant stand under December sowing conditions compared to optimum sowing in Nov 14 (Figure 3.8). Spink et al. (2000) also stated that plant population was significantly reduced under late sowing conditions and grain yield was significantly affected by reduced plant population.

Then at which stage the number of plants per area were reduced for the late sowing conditions? There were three possibilities as below:

1. At germination
2. From germination to emergence
3. Reduction in the number of emerged plants during winter season (winter kill)

The germination was observed one week after the sowing. Although the number of observed seeds was relatively limited, all the seeds had germinated by that time without exception even in the late sowing treatments. Addae and Pearson (1992) reported that the germination of wheat seed was around 96% at 5 °C and 72% at 2 °C indicating that the germination process of wheat is relatively tolerant to cold temperature of these ranges. Based on the observed weather conditions, the daily minimum temperature decreased to below 5 °C from early December in 2014 and late November in 2015 (Figure 3.1c). Daily average air temperature, however, only sporadically dropped below 5 ºC from mid-December to mid-February in 2014-2015, and from mid-January to mid-February in 2015-2016, suggesting that the seeds may have experienced the low temperature at which the germination can be affected only partially and thus it was assumed that the germination process was not affected even in the latest sowing conditions of late December.

Figure 3.8 Aerial view of plant stand of the 2014-2015 experiment under each sowing group (photo was taken in 2015 March 25th of March 2015).

The reduction in the number of emerged plants during winter season was negligible compared to the plant number reduction due to poor emergence (Figure 3.6). The lethal low temperature of wheat was reported as −17.2±1.2°C (Porter & Gawith, 1999). In order to protect critical cell structures and physiological processes during the periods of freezing temperatures, winter cereals including wheat have a mechanism named low temperature acclimation, or winter hardening which is regulated through complex genotypic and environmental interactions (Fowler et al., 1996). Winter wheat needs to be able to gradually acclimatise before a major cold event. If not, there is a possibility of subjecting to the winter kill (Alberta wheat commission, 2013). The acclimation starts when the temperature drops below 10 °C (Fowler et al., 1996). Therefore, winter kill is referred to when plants are not surviving under very low temperatures owing to poor cold acclimation. It has been reported that winter wheat is best adopted to the winter survival if it is between the three leaves to first tiller stage (Alberta wheat commission, 2013).

During the period of the experiment in both years the average air temperature from January to March was below 10 ºC but there was no period in which the air temperature dropped to very low temperature levels close to the lethal levels. Therefore, emerged plants may undergo the cold acclimation in all sowing groups. However, late December sown plants emerged in January therefore, were not in the optimal growth stage. Therefore, winter kill might be the cause of the reduction in the number of emerged plants during winter season. Fowler (1982) has also reported that late sowing resulted in poorly established crop which were more susceptible to winter kill. However, percentage of the number of emerged plants reduction during the winter period was very small compared to the percentage reduction at the emergence.

Therefore, the 2nd possibility, i.e., the plant number was reduced during the stage between germination and emergence seems plausible. In fact Figures 3.3 and 3.4 showed that delayed sowing not only slowed the emergence but also decreased the ultimate emergence percentage by around half. Addae and Pearson (1992) reported from the results of laboratory experiment that emergence of wheat plant was not affected down to 5 ºC, but as it decreased to 2 ºC emergence was reduced to 69 – 76%.

For the purpose of this research, it was aimed at expressing the decrease of emergence percentage due to low temperature by environmental factor(s) or other plant characteristics. Surprisingly there were few such literatures to my knowledge, although the effect of low temperature on the emergence rate like the results of Figure 3.5 is relatively well dealt quantitatively (Lindstrom et al., 1976; Addae & Pearson, 1992). One of the few known examples was the graph expressed with two lines presented by Milthorpe and Moorby (1979). By using the field data of emergence experiment by Harper et al. (1955), they showed the ultimate emergence in y-axis and rate of emergence in x-axis. The ultimate emergence was constant when the rate of emergence is higher than a certain threshold, but decreased linearly below that threshold. The same approach was adopted in the present experiment (Figure 3.7). Unfortunately the data point around the above mentioned threshold was lacking in my data, and it was difficult to approximate the relationship with two lines, and therefore a quadratic relationship was used for the regression. The data points that were used to obtain this relationship comprised of 2 season's data of 2 varieties. With the equation, the emergence percentage can be estimated if the emergence date is known and this knowledge will be used to reinforce the point of weakness of the wheat module of APSIM in the later chapter.

Milthorpe and Moorby (1979) also assumed that the death of the plants at lower temperature mediated by the longer time for emergence might be related to the attack by quasi-parasitic soil fungi, because the similar experiment conducted at laboratories did not have plant mortality even though time taken to emergence was increased.

It was observed that the emergence percentage was lower on Oct 23 (2015) early sowing group compared to that of optimal sowing group although average temperature during the emergence period in early sowing was relatively higher and the number of days taken to the emergence was shorter. There was a high rainfall (45.6 mm; 33% of monthly rainfall) between Nov 1 and Nov 8 in 2015, which coincided with seed germination period. Therefore, reduced emergence may be due to the reduced germination percentage affected by higher rainfall.

3.5 Conclusions

In this study, we elucidated the reasons for decreased grain yield under late sowing conditions. Grain yield reduction by late sowing was attributed to the reduced number of heads per area, which was mainly caused by the reduced emergence, but not by the lowered germination rate nor the winter kill after the emergence. The lower temperature which the late sown seeds has to face not only delayed the emergence date but also the ultimate emergence percentage. The reduction in the ultimate emergence percentage was quantitatively related to the time required from the sowing to the date of emergence with quadratic function which will be used for the model improvement in the later chapter of this thesis.

Chapter 4

Calibration and validation of APSIM crop model for standard sowing conditions in Kanto area, Japan

4.1 Introduction

Estimating model parameters and subsequent validation of the model performances are prerequisite for any crop growth model when the model is used to conduct simulations for cropping systems in specific soil and climatic conditions.

Parameter estimation for system models is referred to as model calibration/parameterization (Wallach et al., 2014) which is being conducted to adjust influential model parameters within their reasonable ranges so that the modeling results become closer to observed data (Wang et al., 2013). There are three types of parameters: the environmental parameters such as soil properties, the crop cultivar parameters, and the management parameters such as sowing date, fertilization, and irrigation rates (Zhao et al., 2014). Soil properties and crop cultivar parameters are used to initialize the model while management parameters are used to modify the cultivation conditions. Soil properties for a specific soil type can be obtained or estimated from soil test results or available soil databases. Therefore, detailed parameter estimation is done mainly to get the crop cultivar parameters, for which trial-and-error method is commonly used for crop models when the specific crop parameters are not available in the published literature. Wang et al. (2013) explain in detail about estimating the crop cultivar parameters using the trial-and-error method and Chen et al. (2010), Mohanty et al. (2012), Balwinder-Sing et al. (2011) also used the same approach for their studies with APSIM crop model.

This study is the first application of APSIM crop model under Japanese condition. Therefore, I conducted the trial-and-error approach (together with some parameters obtained from experimental results) to estimate crop cultivar parameters for two Japanese wheat cultivars grown in Kanto region, Japan.

Model validation is defined as the process of demonstrating that a given model is capable of making sufficiently accurate predictions for specific conditions (soil, climate, cultivar, etc.). The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits (Refsgaard, 1997).

There are two methods to evaluate the model performance for validation: comparing the simulated against observed values graphically and using statistical tests. The evaluation of the model is necessary if the model is to be used for the application purposes (Soltani and Sinclair, 2012). The experiment data other than the ones used for the parameterization should be used for the evaluation of the model. APSIM crop growth model has been used for wheat over a broad range of soils and climates in various parts of the world. But there has been no such use of APSIM model in Japanese conditions so far. Therefore, validation of APSIM model under Japanese conditions has a significant importance when the model potential for applications in research in the future.

This chapter describes the process of calibration and validation of APSIM model for two Japanese wheat cultivars, i.e., Ayahikari (soft wheat) and Yumeshiho (hard wheat), grown in volcanic ash soils in Kanto region, Japan.

4.2 Field experiment data used for model parameterization and validation

Crop phenology, dry matter production at flowering and maturity, LAI, grain yield and GPC data (standard sowing group) from a field experiment conducted between October 2012 and June 2013 was used for the model calibration.

Data from two field experiments conducted in 2014-2015 and 2015-2016 cropping seasons were used for the model validation.

All field experiments were conducted at the Institute for Sustainable Agro-Ecosystem Services (ISAS) (35º44’N, 139º32’E) of the University of Tokyo at Nishitokyo City in Tokyo. It is located in Kanto plain where the volcanic ash soil classified as Typic Melanudand by USDA soil taxonomy, or Andosol by FAO soil classification is dominated.

A summary of the experimental data set is indicated in Table 4.1, and detailed experimental procedures and results of calibration data set and validation data set are explained in Chapter 2 (2012-2013) and Chapter 3 (2014-2015 and 2015-2016).

Table 4.1 Summary of the field experiments used in the model calibration and validation

Year	Cultivars	Type of data used	Sowing group	N treatments	Purpose of use
2012-2013	Ayahikari, Yumeshiho	Date of flowering and maturity,Grain yield, GPC, dry matter production at flowering and maturity, LAI, grain weight,planting density	Satndard (Nov. 08) ,early (Oct. 17), and late (Nov. 29 and Dec. 19)	0, 80, and 150 kg N ha^{-1}	Calibration
2014-2015	Ayahikari, Yumeshiho	Date of flowering and maturity,Grain yield, GPC, dry matter production at flowering and maturity, LAI, planting density, soil water, and soil NO_3^-	Satndard (Nov. 14) and late (Nov. 28, Dec. 12 and Dec. 24)	0, and 160 kg N ha^{-1}	Validation
2015-2016	Ayahikari, Yumeshiho	Date of flowering and maturity,Grain yield, GPC, dry matter production at flowering and maturity, LAI, planting density, soil water, and soil NO_3^-	Satndard (Nov. 13) early (Oct. 23), and late (Dec. 04 and Dec. 22)	0, and 160 kg N ha^{-1}	Validation

4.3 Model Calibration and parameterization

4.3.1 Materials and methods

4.3.1.1 Model initialization

APSIM model version 7.5 was used. The model was initialized with daily weather data (maximum temperature, minimum temperature, solar radiation, and rainfall) for the respective cropping season. Weather data were obtained from a weather station at the experimental location, and soil data (bulk density, saturated water content, drain upper limit, lower limit, and initial NO_3^- and NH_4^+ concentration) obtained from soil analysis. “Fbiom” (Proportion of non-inert C in microbial biomass pool) and “Finert” (Proportion of initial organic C assumed to be inert) soil parameter values were adjusted by comparing with observed dry matter production values at the flowering stage of zero nitrogen conditions (Gaydon et al., 2012) so that APSIM model can capture the original N supply capacity of the soil. No surface residue was assumed as it was in fact the real soil surface conditions in the field at the sowing. Initial soil water content was set arbitrary to 70% of the available water content (between LL and DUL) filled from the top and the sensitivity analysis confirmed that this value does not affect the simulation results significantly. The soil parameters (bulk density, saturated water content, drain upper limit, lower limit, and initial NO_3^- and NH_4^+ concentration) were adjusted based on the data obtained from soil analysis. Then the cultivar parameters/genotypic coefficients for Ayahikari, Yumeshiho were obtained. First, four simulations were created based on sowing dates. Sowing density, sowing depth and row spacing used for the simulation were 300 plants m^{-2}, 25 mm and 190 mm, respectively, based on the field experiment (2012-2013). Detailed information on deriving cultivar parameters are explained under 4.3.1.2

Calibration was conducted in two steps: calibration for phenological parameters (dates of 50% flowering and physiological maturity) and growth parameters (aboveground dry matter at flowering, LAI at flowering, and aboveground dry matter at physiological maturity, grain yield and GPC.

4.3.1.2 Deriving cultivar parameters

APSIM wheat module document explains that wheat crop takes 400 °C days to reach terminal spikelet stage from end of juvenile stage. The daily rate of accumulation of thermal development is sensitive to photoperiod and accumulation of vernalization days. Therefore photoperiod sensitivity and vernalization sensitivity are cultivar specific.

Therefore, we first focused on determining the photoperiod sensitivity (*photop_sens* (P)) and vernalization sensitivity (*vern_sens* (V)) for each cultivar that produces the simulated date of flowering similar to the observed date of flowering (growth stage 68; Zadoks et al., 1974). Wang et al. (2013) also indicated that they have started deriving cultivar parameters with *photop_sens* and *vern_sens* parameters. Before deriving *photop_sens* and *vern_sens* parameters, the model parameter which determines the time lag before linear coleoptile growth starts (*shoot_lag* units), (to adjust the date of emergence) was changed with the calculated thermal time value. This value was calculated as the thermal time taken from sowing to emergence at optimal sowing conditions, using observed emergence data from 2014-2015 and 2015-2016 experiments.

The *photop_sens* and *vern_sens* are in the ranges from one to five (APSIM wheat source code file and Zhang et al., 2012). Therefore, simulation trails were run for all combinations of these parameters in integer with Nov. 8 sowing conditions and calculated the difference between simulated and observed flowering date (DIF). Based on the results the range was further narrowed down to seek the range that produces the lower DIF. Thereafter, simulations were carried out for the narrowed down range for all the sowing times at 0.1 steps for both *photop_sens* and *vern_sens*.

Secondly, to match the simulated date of maturity with the observed date (growth stage 91) the thermal time from the beginning of grain filling to maturity (*tt_start_grain_fill*) was adjusted accordingly with another set of simulation trials. This parameter is the duration of grain filling which is cultivar specific and ranges from 500 to 800 °C days. Further, thermal time from emergence to end of juvenile stage (*tt_end_of_juvenile*) parameter was adjusted to fine tune the simulated date of flowering and maturity.

After that, maximum specific leaf area for delta LAI (*y_sla_max*) was adjusted to improve the LAI simulation and, maximum grain size (*max_grain_size*) and *potential_grain_filling_rate* (grain growth rate during grain fill) parameters were adjusted accordingly to match the simulated grain yield and observed grain yield. Grains per gram stem (*grains_per_gram_stem*) parameter value was calculated from field experiment data of 2014-

2015 experiment and calculated one thousand grain weights were used as *max_grain_size* for both varieties.

This entire procedure is to derive the respective parameters for one cultivar concerned, and therefore the same procedure was repeated for other cultivars.

4.3.2 Results of model calibration

Winter wheat crop is sown by the farmers in Kanto area, Japan in November. Therefore, plants emerge before the winter and become dormant during the winter. Again re-growth starts around March and reached anthesis and maturity in May and June, respectively. Therefore, the four sowing times of the field experiment considered for model calibration consisted of early, mid, slightly late, and late sowing periods. Variation in daily minimum and maximum temperature and, precipitation is showed in Figure 4.1. Precipitation was relatively evenly distributed throughout the season. Although averaged precipitation from January to March was a little bit lower, the precipitation was higher during sowing, and vegetative growth and reproductive periods.

4.3.2.1 Weather data

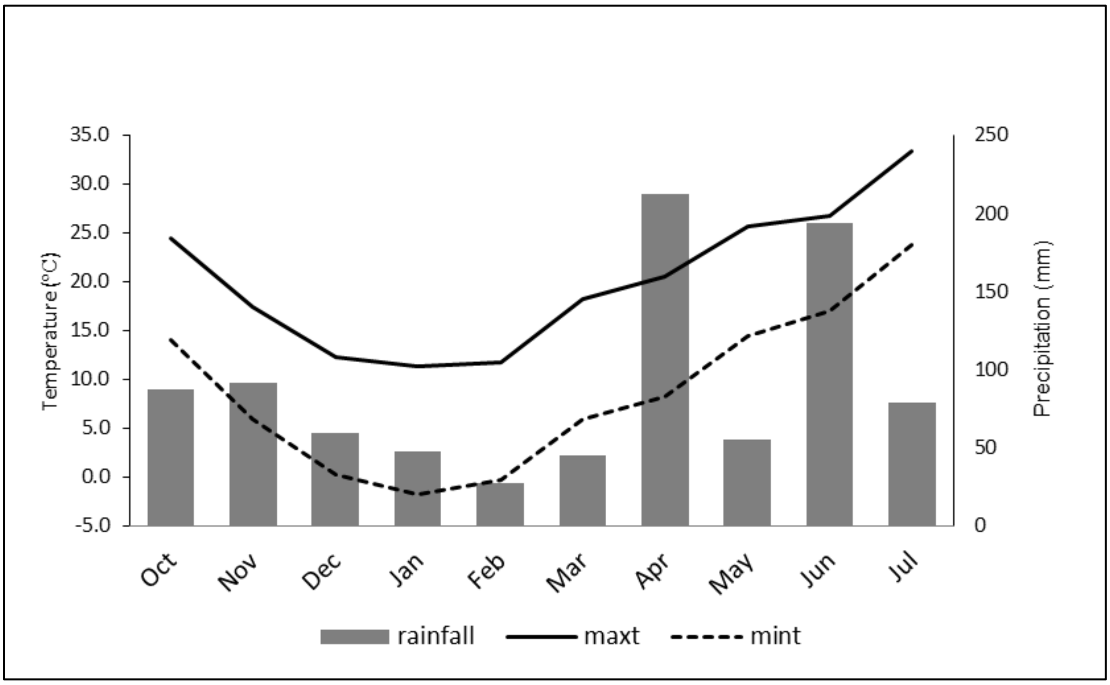


Figure 4.1 Daily maximum and minimum temperature and rainfall averaged over a month. Data recorded by ISAS, Nishi Tokyo, Japan (experiment location).

4.3.2.2 Soil data

Soil type is favorable for plant growth having higher nitrogen supplying capacity (Table 4.2) coupled with ample rainfall.

Table 4.2 Soil nitrogen and pH status at the time of sowing and Fbiom and Finert values obtained after the adjustment to comply with zero nitrogen treatment observed values (for 0-10 and 10-40 and 40-70 soil layers)

Depth(cm)	NO_3^- (ppm)	NH_4^+ (ppm)	pH	Fbiom	Finert
0-10	0.34	0.85	5.7	0.010	0.50
10-40	0.49	0.67	5.8	0.010	0.50
40-70	2.20	0.70	5.7	0.020	0.50
70-100	0.74	0.40	5.7	0.020	1.00
100-130	0.53	0.28	5.6	0.010	1.00

4.3.2.3 APSIM model parameterization

4.3.2.3.1 Parameterization for phenology

Derivation of cultivar parameters or genotype coefficients for phenology was first tried with Nov 8 sowing data (the optimal sowing group). Then adjustments were made for other sowing times. Thus, parameters of vernalization sensitivity (*vern_sens*), photoperiod sensitivity (*photop_sens*), thermal time from emergence to juvenile stage, thermal time from the beginning of grain filling to maturity were determined. The *shoot_lag* unit was obtained from the filed observation. Adjusted parameter values are listed in Table 4.3.

Table 4.3 Phenological parameter values obtained for both cultivars

Phenology Parameters	Default value	Values	
		Ayahikari	Yumeshiho
Sensitivity to vernalization	1.5	2	2
Sensitivity to photoperiod	3	4.3	4.3
Thermal time from emergence to end of juvenile stage (^{0}C d^{-1})	400	300	300
Time lag before linear coleoptile growth starts (^{0}C d^{-1})	40	165	165
Thermal time from beginning of grain filling to maturity (^{0}C d^{-1})	580	750	750

4.3.2.3.2 Parameterization for the production (grain yield, dry matter production, and leaf area index)

The model parameterized for phenology was then run to simulate leaf area index (LAI), dry matter production at flowering, dry matter production at maturity and grain yield. Since the simulated results overestimated these observed values, some model parameters related yield were adjusted with trial and error approach. The target parameters I chose were, specific leaf area (at flowering stage), *potential_grain_filling_rate*, *grains_per_gram_stem*[1], *maximum_ grain_size*. The adjusted parameters are shown in Table 4.4. Out of them,

[1] In APSIM, the number of the grains per plant is set by multiplying this parameter (*grains_per_gram_stem*) with the stem dry weight at flowering.

grains_per_gram_stem and *maximum_grain_size* were calculated values based on observed field data. The other two parameters were obtained by trial-and-error method.

Table 4.4 Adjusted parameter values for each cultivar to receive better simulation results for LAI, dry matter production and grain yield.

Growth Parameters	Default value	Values	
		Ayahikari	Yumeshiho
Maximum specific leaf area for delta LAI	27000-22000	20000-14000	22000-16000
Grains per gram stem	25	61	57
Maximum grain size	0.041	0.035	0.032
Potential grain filling rate	0.002	0.0025	0.0022

4.4 Model validation

4.4.1 Materials and methods

4.4.1.1 Model initialization

As it was indicated in Table 4.1, 2014-2015, and 2015-2016 experimental data were used for the model validation for phenology, grain yield, GPC, LAI, dry matter production at flowering and dry matter production at maturity. Besides, observed data for soil NO_3^- and soil water from 2014-2015 and 2015-2016 experiments were validated. For the validation, separate APSIM simulations were run for each year's sowing and nitrogen management conditions using the calibrated model.

4.4.1.2 Methods to obtain the simulated data

Data from two field experiments conducted in 2014-2015 and 2015-2016 cropping seasons were used for the model validation. For both Ayahikari and Yumeshiho wheat cultivars, using the experimental procedures of two experiments, simulations were conducted to obtain the simulated date of flowering and maturity (phenology), dry matter production, LAI, grain yield and grain protein content with the parameterized model configuration.

4.4.1.3 Methods of model evaluation

4.4.1.3.1 Comparison of observed and simulated values

Observed and simulated phenology, grain yield, dry matter production, leaf area index (LAI) grain protein content, soil nitrate, and soil water were compared graphically to observe the fitness of observed and model-simulated data and to see whether the model could capture the trends of observed data.

4.4.1.3.2 Quantifying the model performances

The model performances were quantified using four statistical indices which have been widely used in the previous reports. (e.g., Asseng et al., 1998, 2000; Wang et al., 2013; Chen et al., 2010; Zhang et al., 2012; Balwinder-Singh et al., 2011; Mohanty et al., 2012; Wu et al., 2013).

Root mean square error (RMSE), relative root mean square error (RRMSE), slope (*m*) of a best-fit regression line forced through the origin and modelling efficiency (ME) are the four statistical parameters used for the model validation.

The slope (*m*) of the best-fitted regression line forced through the origin quantifies the possible over or underestimation (if it is not forced through the origin the slope is not relevant for the test; Asseng et al., 1998). The root mean square error (RMSE) gives a measure of the absolute magnitude of the error. RMSE has the same units of measured and simulated values. The RRMSE is a meaningful measure to compare simulation quality of data with highly different averages (ex. yield in kg ha^{-1} and LAI), and it is independent of the unit used. RRMSE is calculated by dividing the RMSE by the mean of the observed values and expressed as a percentage (Asseng et al., 1998; Wu et al., 2013; Wallach et al., 2014). The modelling efficiency (ME) compares the deviations between predicted and observed values to the variance of the observed values. Figure 4.1 shows the equations for calculating RMSE and ME

$$\text{Root mean square error (RMSE)} = \sqrt{\left(\sum_{i=1}^{i=n} \frac{(P_i - O_i)^2}{n}\right)}$$

$$\text{Modelling efficiency (ME)} = 1 - \left[\frac{\sum_{i=1}^{i=n}(P_i - O_i)^2}{\sum_{i=1}^{i=n}(O_i - \bar{O})^2}\right]$$

where P_i, predicted value, O_i, observed value, $\bar{O}$, mean of the observed values, n, number of observation.

(Source of equations: Mohanty et al., 2012)

Figure 4.2 The equations for calculating RMSE and ME

RMSE closer to 0 denotes the best model performance (lower the RMSE value better the performance), ME = 1 denotes perfect match of predicted and observed values and ME = 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty < ME < 0$) occurs when the observed mean is a better predictor than the model. ME values between 0 and 1 are generally viewed as acceptable levels of performance and model performance can be evaluated as satisfactory if ME > 0.5, good if ME > 0.65 and, very good if ME > 0.75 (Moriasi et al., 2007).

A variant of the RMSE is the RRMSE. Lower the RRMSE is, lesser the residual variance (residual variance measures how accurately the model's predictions match with actual values) is. Model accuracy was considered very good if RRMSE <10%, good if 10% < RRMSE < 20%, fair if 20% < RRMSE < 30% and poor if RRMSE > 30%, (Jamieson et al., 1991, Magaia et al., 2017).

Model performance was tested across all sowings for phenology. But grain yield, GPC, dry matter production and LAI were tested for optimum sowing conditions first and then for all sowing groups (including early and late sowing conditions).

4.4.2 Results (Model validation)

4.4.2.1 Validation for phenology

Model-predicted and observed date of flowering and maturity from 2014-2015 and 2015-2016 experiments fitted well across early, standard and late sowing conditions (Figure 4.3) with RMSE ranged from 1.5 to 4.9 days for flowering time and from 0.7 to 6.5 days for maturity (Table 4.5). RMSE were higher in 2015-2016 for both cultivars (4.9 days for date of flowering and 6.5 days for date of maturity). RRMSE was lower than 6% for the date of flowering and maturity in both Ayahikari and Yumeshiho which confirm the lesser residual variance. ME values were close to one showing the good model performance (Table 4.5).

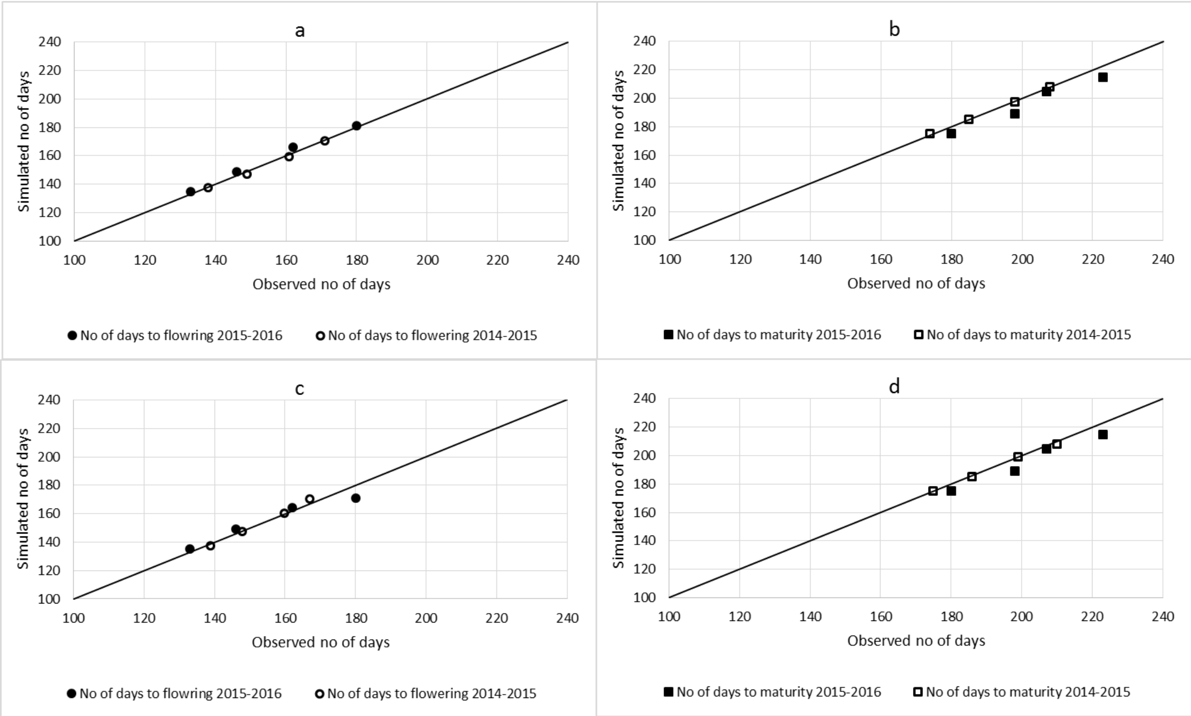


Figure 4.3 Simulated and observed number of days to flowering and maturity in 2014-2015 and 2015-2016 for Yumeshiho (a-b) and Ayahikari (c-d). Each data point represents different sowing group (Nov. 14, Nov. 28, Dec. 12 and, Dec. 24 in 2014-2015 and Oct. 23, Nov. 13, Dec. 04 and Dec. 22 in 2015-2016). The continuous line is 1:1 line.

4.4.2.2 Validation results for grain yield, GPC, dry matter production and LAI (optimum sowing)

Observed grain yields varied between 170 and 468 g m^{-2} for Ayahikari and, between 163 and 517 g m^{-2} for Yumeshiho. APSIM model simulated the grain yield very well with a good agreement between observed and simulated values (Figure 4.4) for both cultivars. APSIM model could simulate the grain yield response of Yumeshiho and Ayahikari to N application for a wider range of N supply (from 0 to 160 kg N ha^{-1}) (Figure 4.5). Model evaluation indices (Table 4.6) RMSE (23 g m^{-2} for Ayahikari and 48.2 g m^{-2} for Yumeshiho), RRMSE (7.2 for Ayahikari and 15.7 for Yumeshiho), and ME (0.97 for Ayahikari and 0.88 for Yumeshiho) confirm the robustness of the model estimating the grain yield with higher accuracy.

Observed GPC varied between 10.4 and 13.5 % for Ayahikari and, between 11.8 and 15.1 % for Yumeshiho. Simulation of GPC was better in Yumeshiho (RMSE 1.4%, RRMSE 10.5) than Ayahikari (RMSE 1.9 %, RRMSE 15.8). APSIM model could simulate well the variation of observed GPC in response to the wider range applied N for both cultivars (Figure 4.6). Therefore, GPC validation is acceptable for both cultivars. However, as shown in Figure 4.4 and by *m* values, the model tends to slightly overestimate GPC for Ayahikari (*m* 1.13) and underestimate that for Yumeshiho (*m* 0.95).

Figure 4.4 shows the observed and predicted LAI. APSIM model could simulate the observed LAI changes with an RMSE 0.5 for both Ayahikari and Yumeshiho. ME values (Ayhikari 0.67, Yumeshiho 0.57) (Table 4.6) showed that there is a good fitness between simulated and observed LAI.

As shown in Figure 4.4, dry matter production at maturity (except for some data points) fitted close to one to one line than dry matter production at flowering. ME also showed that goodness of fitness better in dry matter production at maturity and acceptable for dry matter production at flowering (0.33 and 0.89 for dry matter production at flowering and maturity respectively for Ayahikari and 0.76 for dry matter production at maturity for Yumeshiho). However, dry matter production at flowering for Yumeshiho (ME -0.2) showed a tendency to overestimate (m = 0.12) (Table 4.6).

4.4.2.3 Model performances for estimating soil nitrate concentration

The model could capture the observed soil nitrate dynamics at 0-30 cm soil layer (topsoil layer) in both years of validation (Figure 4.8). The observed range of soil NO_3 was 3.9-40.3 g kg^{-1}. Model error was 2.18 g kg^{-1} RMSE with ME 0.94 (Table 4.6).

4.4.2.4 Model performances for grain yield, GPC, dry matter production and LAI (across all sowing conditions including early and late sowing)

After validation of the model for optimum sowing conditions, it was further tested for across all sowing conditions in 2014-15 and 2015-16. The results showed that the model performances went down when the data of late sowing conditions were included. The goodness of fitness reduced and RMSE increased for all growth parameters concerned (Table 4.6 and Figure 4.7).

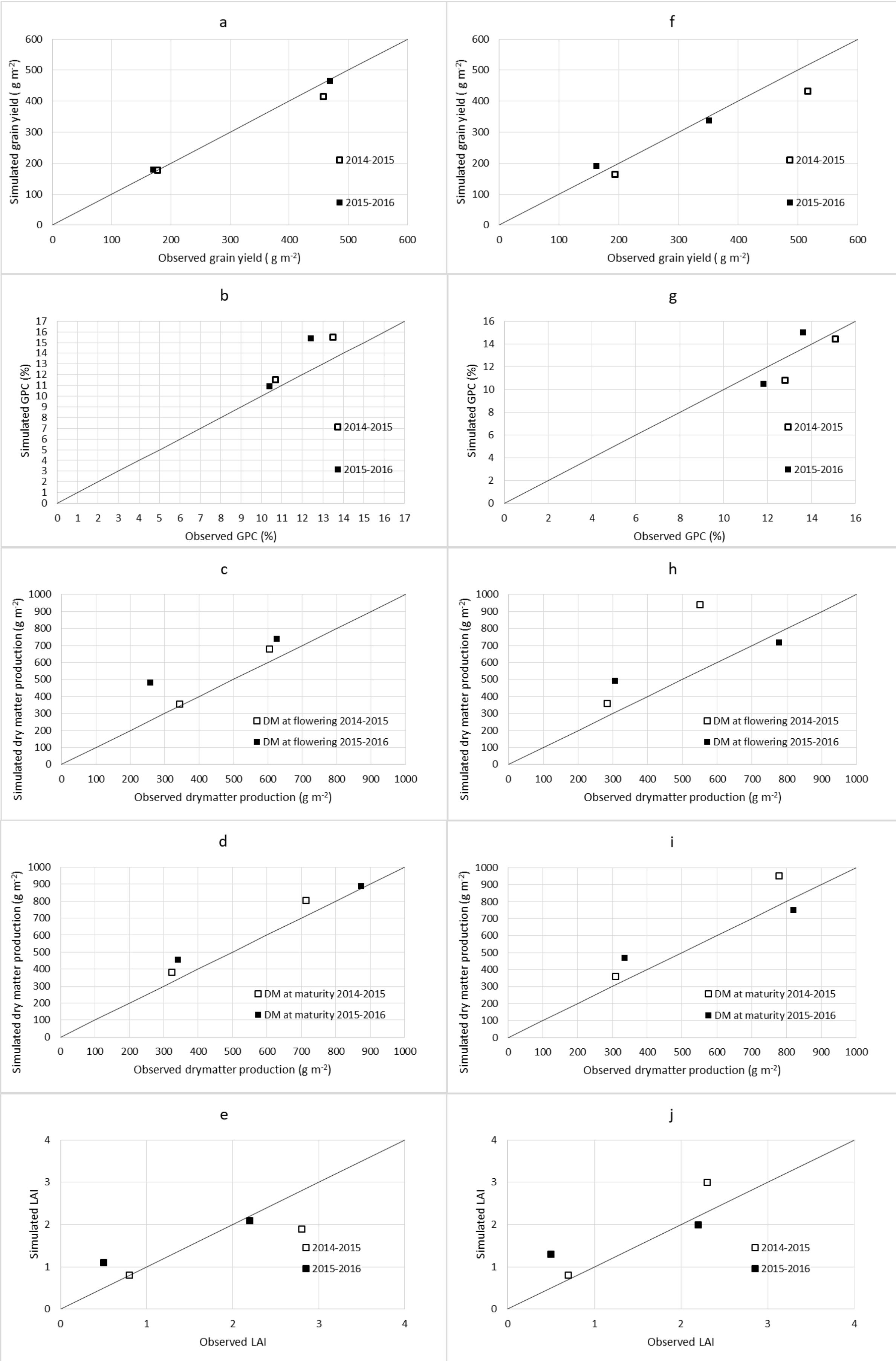

a
Simulated grain yield (g m-2)
Observed grain yield (g m-2)
2014-2015
2015-2016
f
Simulated grain yield (g m-2)
Observed grain yield (g m-2)
2014-2015
2015-2016
b
Simulated GPC (%)
Observed GPC (%)
2014-2015
2015-2016
g
Simulated GPC (%)
Observed GPC (%)
2014-2015
2015-2016
c
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at flowering 2014-2015
DM at flowering 2015-2016
h
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at flowering 2014-2015
DM at flowering 2015-2016
d
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at maturity 2014-2015
DM at maturity 2015-2016
i
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at maturity 2014-2015
DM at maturity 2015-2016
e
Simulated LAI
Observed LAI
2014-2015
2015-2016
j
Simulated LAI
Observed LAI
2014-2015
2015-2016

Figure 4.4 Simulated and observed grain yield, GPC and dry matter production at flowering and maturity, and LAI for Ayahikari (a,b,c,d,e) and Yumeshiho (f,g,h,i,j) in 2014-2015, and 2015-2016 at optimal sowing. The black line is 1:1 line.

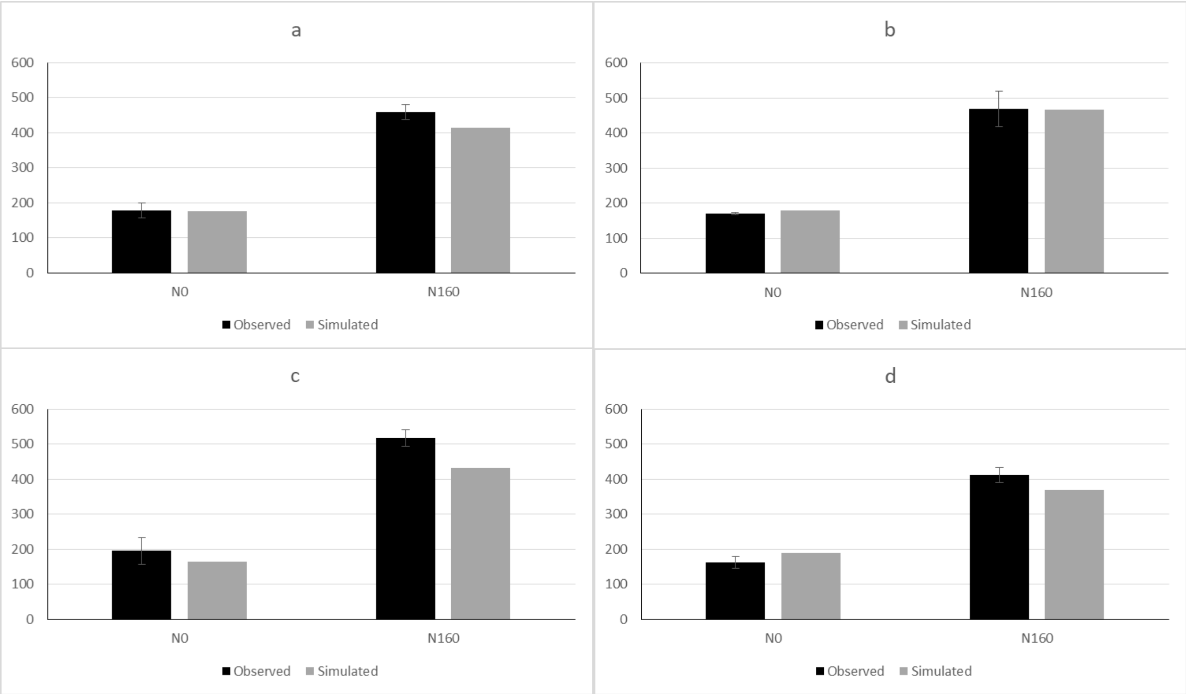


Figure 4.5 Simulated and observed grain yield in response to two different N treatments for Ayahikari (a-b) and Yumeshiho (c-d). "a" and "c" represent the 2014-2015 data and "b," and "d" represents the 2015-2016 data.

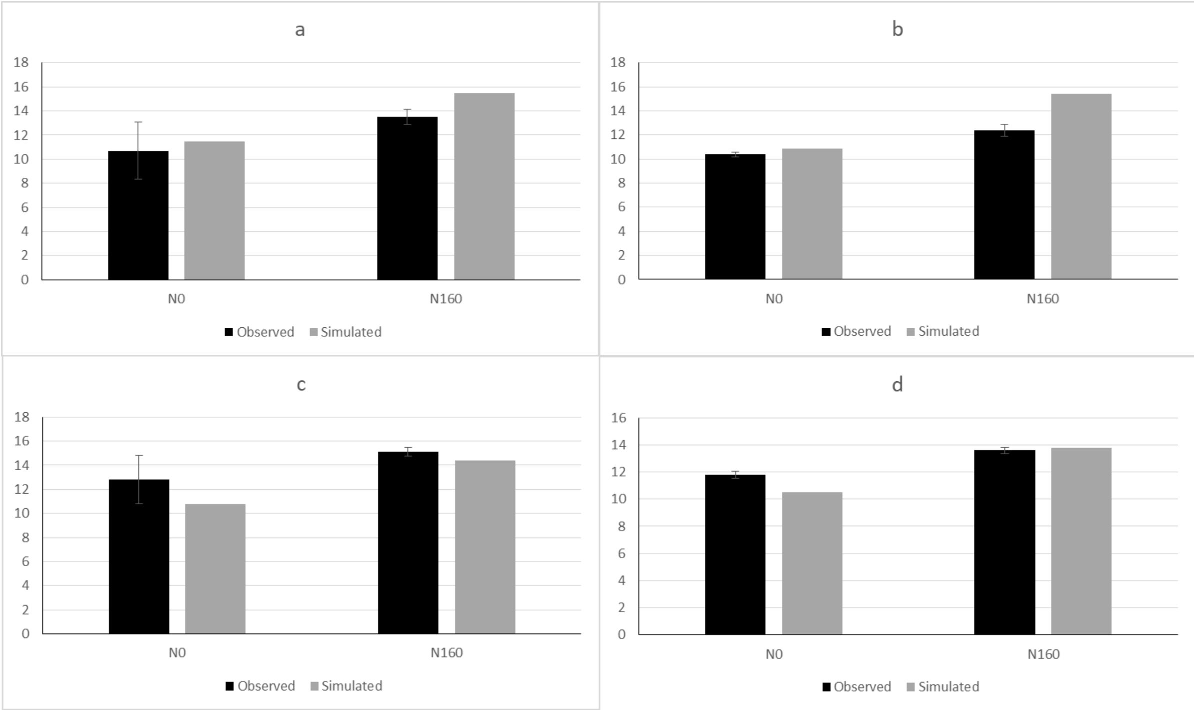


Figure 4.6 Simulated and observed GPC in response to two different N treatments for Ayahikari (a-b) and Yumeshiho (c-d). “a" and "c" represents the 2014-2015 data and "b," and "d" represents the 2015-2016 data.

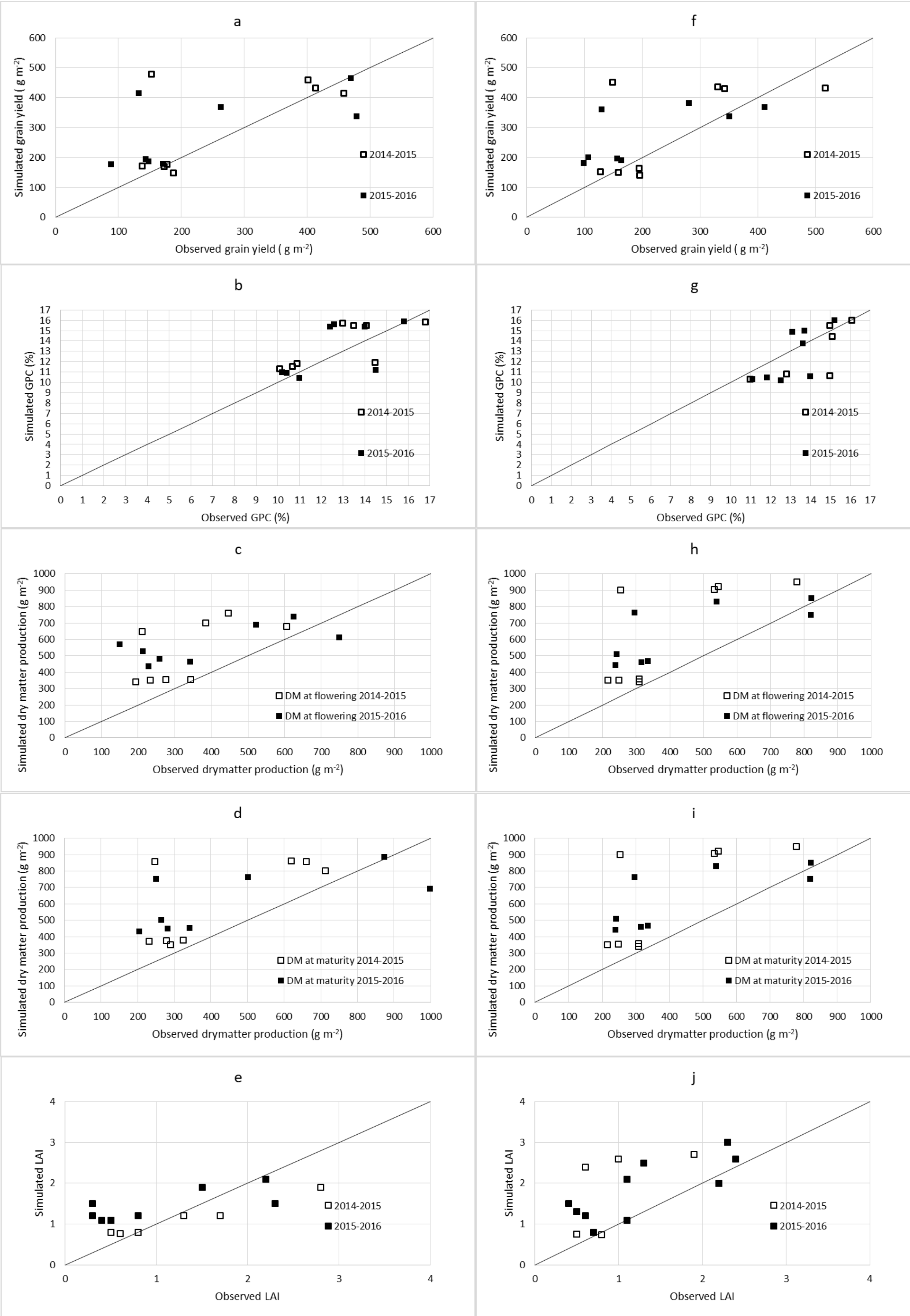

a
Simulated grain yield (g m-2)
Observed grain yield (g m-2)
2014-2015
2015-2016
f
Simulated grain yield (g m-2)
Observed grain yield (g m-2)
2014-2015
2015-2016
b
Simulated GPC (%)
Observed GPC (%)
2014-2015
2015-2016
g
Simulated GPC (%)
Observed GPC (%)
2014-2015
2015-2016
c
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at flowering 2014-2015
DM at flowering 2015-2016
h
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at flowering 2014-2015
DM at flowering 2015-2016
d
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at maturity 2014-2015
DM at maturity 2015-2016
i
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at maturity 2014-2015
DM at maturity 2015-2016
e
Simulated LAI
Observed LAI
2014-2015
2015-2016
j
Simulated LAI
Observed LAI
2014-2015
2015-2016

Figure 4.7 Simulated and observed grain yield, GPC and dry matter production at flowering and maturity, and LAI for Ayahikari (a,b,c,d,e) and Yumeshiho (f,g,h, i,j) in 2014-2015, and 2015-2016 for all sowing groups. The continuous line is 1:1 line.

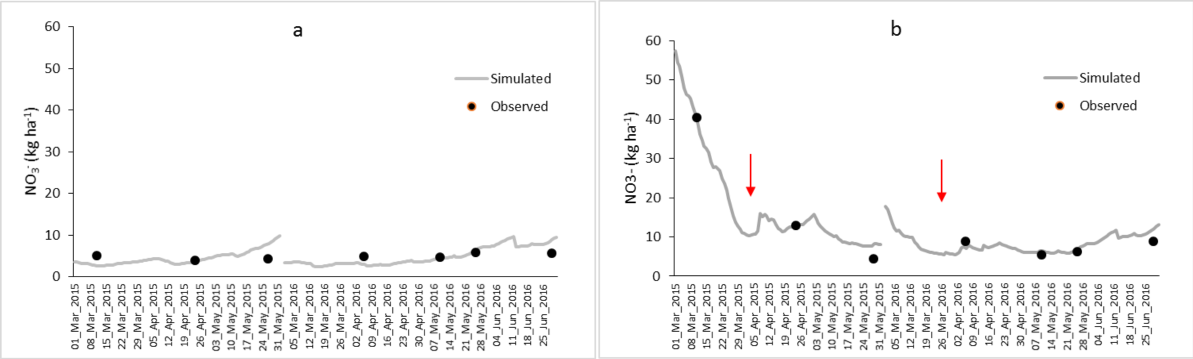


Figure 4.8 Simulated and observed soil NO_3^- during the 2014-2015 and 2015-2016 cropping seasons. The measurement was taken from zero N plots (a), and N applied plots (160 kg N ha^{-1} per season; 120 kg N ha^{-1} at sowing and 40 kg N ha^{-1} at stem elongation stage) (b). Soil layer is 0-30 cm. Red arrows denote date of split N application at stem elongation stage.

Table 4.5 Summary of APSIM model performances for Kanto area (Volcanic ash soils) in Japan for Phenology across all sowing groups of 2014-2015 and 2015-2016

Model attribute	Observed range	RMSE[a]	RRMSE[b]	ME[c]	*m* [d]
Ayahikari					
Number of days to flowering*					
2014-2015	139-167	1.8	1.21	0.96	1
2015-2016	133-180	4.9	3.1	0.92	0.99
Number of days to maturity*					
2014-2015	175-210	1.11	0.58	0.99	0.99
2015-2016	180-223	6.5	3.2	0.81	0.97
Yumeshiho					
Number of days to flowering*					
2014-2015	138-171	1.5	1.02	0.98	0.99
2015-2016	133-180	4.9	3.1	0.92	0.99
Number of days to maturity*					
2014-2015	174-208	0.7	0.36	0.99	0.99
2015-2016	180-223	6.5	3.2	0.81	0.97

[a] Root mean square error

[b] Relative root mean square error

[c] Model efficiency

[d] Slope (m) of a best-fit regression line forced through the origin

*Observed across four sowing groups

Table 4.6 Summary of APSIM validation for Kanto area in Japan for growth parameters. The results of two different analysis were compared (one with the data at optimum conditions only, the other with the data from all sowing groups).

	Optimal sowing					Across all sowings				
Model attribute	**Observed range**	**RMSE[a]**	**RRMSE[b]**	**ME[c]**	***m*[d]**	**Observed range**	**RMSE[a]**	**RRMSE[b]**	**ME[c]**	***m*[d]**
Ayahikari										
Grain yield (g m^{-2})	170 - 468	23	7.2	0.97	0.96	87-478	121.5	48.6	0.2	1.05
GPC (%)	10.4 - 13.5	1.9	15.8	-1.1	1.13	10.1-16.8	1.9	14.6	0.14	1.04
LAI	0.5 - 2.8	0.5	34.4	0.67	0.82	0.3-2.8	0.6	54.7	0.4	0.89
Drymatter at flowering (g m^{-2})	259 - 625	130.7	28.5	0.33	1.18	150-749	243.3	64.8	-0.81	1.31
drymatter at maturity (g m^{-2})	324 - 873	77.9	13.8	0.89	1.1	204-997	259.3	58.6	-0.12	1.18
Yumeshiho										
Grain yield (g m^{-2})	163 - 517	48.2	15.7	0.88	0.88	99-517	113.1	48.6	0.11	1.1
GPC (%)	11.8 - 15.1	1.4	10.5	-0.3	0.95	11-17.9	2.5	17.4	-0.5	0.9
LAI	0.5 - 2.3	0.5	38.1	0.57	1.15	0.4-2.4	0.9	76.7	-0.6	1.36
Drymatter at flowering (g m^{-2})	283 - 777	221	46.1	-0.2	1.2	173-777	291.6	77.6	-1.87	1.5
drymatter at maturity (g m^{-2})	308 - 819	116.9	20.8	0.76	1.09	216-821	276.1	64.9	0.7	1.34
Soil NO_3^- N (0-30 cm) g kg^{-1}	3.9 - 40.3	2.18	25.2	0.94	0.96					

[a] Root mean square error

[b] Relative root mean square error

[c] Model efficiency

[d] Slope (m) of a best-fit regression line forced through the origin

4.5 Discussion

4.5.1 Model calibration

The optimum sowing time, as well as the farmers' general practice for winter wheat in Kanto area of Japan, is considered to be early to mid or mid to late November. Results of the 2012-2013 field experiment also coincided with this sowing time, as Nov 8 sowing showed the best performance in comparison to the other three sowing times. In the Nov 8 sowing, both hard and soft wheat cultivars showed a good response to the nitrogen fertilizer applications and achieved the highest yields, i.e., Ayahikari and Yumeshiho achieved 606.9 g m^{-2} and 619.4 g m^{-2} respectively at the highest nitrogen application rate (150 kg N ha^{-1}). Also, these two cultivars are recommended for the Kanto area in Japan. Thus, we used Nov 8 sowing group data as the baseline for the calibration process.

First, model calibration for phenology cultivar parameters was initiated with the trial-and-error method by using the field experiment results of Nov 8 sowing group data. Then they were combined with the early and late sowing group data to obtain the phenology related parameters that are capable of facilitating phenology simulations over various sowing times. Next, I derived growth-related parameters. These derived cultivar parameters were not available in the existing literature as this study is the first attempt to apply APSIM model in Japanese conditions. Thus, parameter values obtained in this study would be a good source for future research work.

Of the phenology parameters concerned, "sensitivity to vernalization (*vern_sens*)" and "sensitivity to photoperiod (*photop_sens*)" are related with flowering time, and "thermal time from the beginning of grain filling to the maturity (*tt_start_grain_fill*)" is related to the date of maturity. "Thermal time from the emergence to the juvenile period (*tt_end_of_juvenile*)" is related to early growth stage and affects the flowering date indirectly. For both cultivars, the obtained vernalization sensitivity was two that indicates low vernalization requirement. Such low vernalization sensitivity also suggests that these cultivars are more spring types. Kiribuchi-Otobe, (2009) and Yoshida et al. (2001) also indicated that Yumeshiho and Ayahikari are spring varieties with a low degree of winter habit. After setting phenology parameters, overall simulation capability of the model for phenology was improved across early, mid and late sowing groups of both cultivars.

Once the parameterization is done for the phenology, the model predictions were checked for the dry matter production (at flowering and maturity), leaf area index (LAI) and grain yield. In the initial stage, overall model predictions were overestimated, especially dry matter productions at maturity, LAI and grain yield. Therefore, parameterization was continued further with more growth-related parameters (Table 4.4) until model predictions develop into reasonable values with lower error. Asseng et al. (1998, 2000) also used similar parameters to my study in the model parameterization process. Parameter adjustments were initiated with specific leaf area values (*y_sla_max*) followed by grains per gram stem (*grains_per_gram_stem*), maximum grin size (*max_grain_size*) and, potential grain filling rate (*potential_grain_filling_rate*). With this parameterization, model predictions for the standard sowing time (Nov-8) were significantly improved. However, with the calibrated data set APSIM model still overestimated the grain yield, dry matter production and leaf area index for late sowing conditions (Dec 19).

On the other hand, I observed that the number of the remaining plants during the winter season was notably lower in the late sowing treatments than in the optimum sowing time treatment of Nov 8. As discussed in Chapter 3, it was found that the decrease of the number of plants was mainly due to poor emergence caused by longer emerge duration owing to low temperature. However, in APSIM wheat model no algorithm accounts for the reduction of plant number that occurs due to low temperature affected reduced emergence. Zhang et al. (2012)

found that when using APSIM, the errors of phenology and yield simulations increase with the delay in sowing date.

Detailed sensitivity analysis conducted by Zhao et al. (2014) confirmed that the parameters I used for the calibration are the most appropriate parameters due to two reasons. Firstly, they highlighted that the yield predictions are most sensitive to the cultivar parameters that determine the yield component (*grains_per_gram_stem, max_grain_size*, and *potential_grain_filling_rate*) and the phenology parameters that determine length of the reproductive stages (*thermal time from floral initiation to flowing* and *tt_start_grain_fill*). Secondly, they showed that all ten cultivar parameters affect biomass, but amongst which the parameters of *vern_sens* and *thermal time from floral initiation to flowering* are the most influential.

Japanese soil parameters are not included in APSIM soil database. Hence, one of the soil types that have very close soil characteristics of the experiment location was selected. Then the soil type chosen was modified based on a field soil sample analysis to represent volcanic ash soil type. Fbiom soil parameter values (represents the soil microbial biomass fraction) and Finert soil parameter values (represents the organic carbon fraction which is not decomposing), in APSIM soil parameters, were adjusted (Probert et al., 1998) to make sure that parameterized soil is capable enough to capture indigenous N supply capacity of volcanic ash soils, Fbiom and Finert values were altered until the simulated indigenous N supply in the zero-N treatments allowed close simulation of the measured biomass data at the flowering of zero N treatment of Nov. 8 sowing group. Gaydon et al. (2012) followed a similar method when calibrating Fbiom and Finert using the results of field soil data analysis.

4.5.2 Model validation

Results of the model performance tests confirmed that APSIM model could be applied for Japanese wheat cultivars that grow under the climatic and soil conditions in Kanto area and in other areas in Japan that has similar soil and climatic conditions. Some inter-seasonal variations of the rainfall and temperature that were observed in the validation data set of two cropping-seasons facilitated further meaningful validation of the model (weather data information of validation data set is explained in Chapter 3). This validation was found to be applicable for predicting phenology under early, optimum and late sowing conditions as well as for predicting grain yield, GPC, dry matter production and LAI, mainly at optimum sowing time conditions. Further model improvement that addresses the plant number reduction caused by poor emergence under late sowing conditions is needed to apply this model under late sowing conditions.

Validation results of this study for grain yield showed that RMSE of 23 g m^{-2} for Ayahikari grain yield and 48.2 g m^{-2} for Yumeshiho grain yield. Asseng et al. (1998 and 2000), Chen et al. (2010) and Balwinder-Sing et al. (2011) who conducted successful validation of APSM model under standard sowing conditions for wheat in Western Australia, Netherland, China (North China Plain) and India, reported RMSE values of 40 gm^{-2}, 80 g m^{-2}, 83 gm^{-2} and 55 g m^{-2} respectively for grain yield.

We obtained RMSE of 77.9 g m^{-2} (for Ayahikari) and 116.9 g m^{-2} (for Yumeshiho) for total dry matter production at maturity and RMSE of 0.5 (for both Ayahikari and Yumeshiho) for LAI. Asseng et al. (1998 and 2000) reported RMSE of 80 g m^{-2} and 120 g m^{-2} for dry matter production at maturity and 0.6 and 1.2 for LAI. Furthermore, Chen et al. (2010), reported RMSE of 140 g m^{-2} and 1.6 of for dry matter production and LAI respectively.

RMSE of GPC percentage validation for Ayahikari and Yumeshiho were 1.9 % and 1.4 % respectively. For GPC %, Asseng et al. (1998 and 2000) obtained RMSE of 3.2 % and

1.6 %. After introducing new grain protein routine by Asseng et al., 2002, their RMSE reduced (between 1.5% and 2 %) for temperate marine and Mediterranean regions. This proves that grain protein validation of my study is consistent.

Therefore, as indicated in above comparisons, my results are within the compatible range with the existing reports on APSIM model validation. Furthermore, the results (Table 4.6) indicated higher model efficiency (ME) for both cultivars regarding phenology, grain yield, LAI, dry matter production at maturity. Nevertheless, it showed a lower ME for the GPC percentage (Table 4.6). However, the model performance of GPC is acceptable for two reasons, i.e., validated model could capture the GPC variation in response to the different amount of N applied in a wider range, and the RMSE fell within in the range that was obtained by previous studies.

Further, APSIM model could capture the soil nitrate dynamics in the topsoil layer (0-30 cm) in both years of validation (Figure 4.8), with a higher model efficiency (ME 0.96) for a wide range of observed values. Also, the actual change in soil nitrate in response to fertilizer application was also represented in the model simulation. Moreover, APSIM model could simulate the grain yield and GPC very close to that of observed under zero N conditions. These results confirm that the model reliably incorporated the indigenous N supply of volcanic ash soils. Thus, the validation confirmed that the parameters derived from the calibration were appropriate and can be used effectively for prediction of wheat phenology and growth parameters (yield, GPC, dry matter production and LAI) under soil and climatic conditions in Kanto region, Japan.

Considering all the model performance indices, comparisons between observed and simulated yields, and response of GPC to N application and validation of soil nitrate, we have a confidence that APSIM model could be utilized successfully to support decision making in N management as well as to aid simulation studies related to phenology, grain yield and GPC of Ayahikari (soft wheat) and Yumeshiho (hard wheat) cultivars grown in volcanic ash soils of Kanto area in Japan.

Although prediction of phenology can be applicable for optimum and late sowing conditions, further improvements would be necessary for the prediction of yield, GPC and dry matter production under late sowing conditions. Because, when the validation was conducted across sowing groups, the model performance for yield, GPC and dry matter production diminished. (Figure 4.7 and Table 4.6).

Next chapter (Chapter 5) explains the details of model improvement conducted by combining APSIM model with an empirical model to improve the prediction accuracy of grain yield and GPC under late sowing condition.

Chapter 5

Model improvement to simulate wheat growth under late sowing and the validation of the APSIM model across optimum and late sowings

5.1 Introduction

In the previous chapter, the results of the model validation elucidated that calibrated APIM wheat model could simulate wheat phenology irrespective of the sowings dates. The model, however, could not simulate the growth parameters (grain yield, GPC, dry matter production, and LAI) across the sowing dates because it overestimated these parameters in late sowing conditions.

Under the field conditions in Kanto region in Japan, the grain yield of autumn sown wheat was reduced and GPC was increased when the sowing was conducted in late December (Chapters 2 and 3). Further, the careful studies on seed emergence revealed that the yield reduction by late sowing was attributed to the reduced number of heads per area mainly caused by the reduced emergence (Chapter 3). The low temperature which the late-sown seeds had to face not only delayed the emergence but also reduced the ultimate emergence percentage.

However, the APSIM model does not have the algorithm to reduce the number of plants when the sowing was done under the low temperature conditions (APSIM wheat model document). The situation is same for several other major crop growth models such as Sirius, NWheat, and STICS. CERES model has the function to deal with "winter kill" after the emergence under extremely low temperatures (Savdie et al., 1991). But as was discussed in Chapter 3, the wheat growing conditions in Kanto region is not so severe where only the emergence percentage is reduced but once emerged plants could survive during the winter season, and therefore the winter kill is not the predominant factor. Hence the approach in the CERES model cannot be applied for this situation.

Therefore, in this chapter, first I aimed at introducing a new algorithm to APSIM wheat model to reduce the plant density when the sowing and emergence should take place at low temperature with the purpose to increase the precision of the model under the delayed sowing conditions for winter wheat. Then, the model was revalidated for the growth parameters (grain yield, GPC, dry matter production, and LAI) across early, optimum and late sowing conditions.

5.2 Materials and Methods

5.2.1 Model improvement to change plant density according to the time to emergence

It is indicated in the APSIM wheat module document that, “In the current version of APSIM-Wheat, wheat plants are assumed to be uniclum (i.e., with a single stem), meaning that tillering is not simulated *per se*. While a node corresponds to a phytomer on the main stem, it represents all the phytomers that appear simultaneously on different tillers (i.e., cohort of leaves) in the real world” (APSIM wheat module document). The number of plants per unit area is an input parameter in APSIM, and it is fixed throughout the simulation. After the emergence, this number is used for simulating the total biomass and grain yield. There is no algorithm in APSIM wheat to change the plant density when it is affected at emergence (Bangyou Zheng, personal communication, December 12, 2015).

In Chapter 3, an equation was derived to calculate the ultimate emergence percentage from the time required from the sowing to the date of emergence. This function was added to the “Sow on fixed date” module in the manager module of APSIM model as indicated in 5.2.1.1.

5.2.1.1 Modification of algorithm

The frequently used “Sow on a fixed date” module in APSIM sets the plant density and other sowing rules such as sowing depth, cultivar and row spacing by using corresponding input parameters when the “today” is the specified sowing date (see Box 5.1).

Box 5.1 Sowing rule and new model codes

```
<!------“Sowing rule”------------------------------------->
if (today = date('[date]') then
     [crop] sow plants =[density], sowing_depth = [depth],
     cultivar = [cultivar], row_spacing = [row_spacing],
     crop_class = [class]
endif

<!------“new model codes connected to sowing rule”------------------------------------ >

if (wheat.stage = 3) then                                    (1)
    daystoemerge=DaysAftersowing                             (2)
    x= (1/daystoemerge)                                      (3)
    y= [density]*((-2357.9*x^2) + 576.6*x +12.328)/100       (4)

     wheat kill_stem plants= y                               (5)
endif
```

Then the new 5 lines were added.

Line 1: wheat stage = 3 in APSIM indicates that the crop stage reached to "emergence" in the do loop of the whole simulation of the time step of each day.

Line 2: a new model parameter, the number of days from sowing to emergence (`daystoemerge`) is defined as the number of days after sowing (`DaysAftersowing`) on that day. With this new command, model calculates the number of days from sowing to emergence.

Line 3: the rate of the emergence "`x`" is calculated from `daystoemerge`.

Line 4: corrected planting density at emergence (`y`) is calculated from the rate of emergence (`x`) and original sowing rule (`[density]`) by using the function derived from the regression in Figure 3.7 (Chapter 3).

Line 5: finally, "plant kill function" (`wheat kill_stem`) is used to adjust the plant density (plants) by using `y`.

5.2.2 Testing and revalidation of the improved model

5.2.2.1 Testing of the improved model

The improved model was tested with the Dec 19, 2012 late sowing data of the parameterization dataset (described in Chapter 4) for its accuracy of predicting the growth parameters under late sowing conditions for both Ayahikari and Yumeshiho. Re-parameterization was conducted with trial and error simulations for Yumeshiho with a plant related parameter "<y_leaves_per_node>" since it was still found that LAI and dry matter production and grain yield were over estimated by the model to some extent.

5.2.2.2 Re-validation of the APSIM model after the improvement

By following the procedures described in 4.4.1.2 and 4.4.1.3, the improved model was validated again for all sowing dates of 2014-2015 and 2015-2016 seasons for grain yield, GPC, dry matter production at both flowering and maturity, and LAI, for both cultivars, Ayahikari and Yumeshiho.

5.3 Results

It was confirmed that planting density was reduced from 300 (original planting density) to 77 plants per m^2 when the improved model was used for the Dec 19, 2012 sowing data of the parameterization data set (2012-2013). Table 5.1 shows the new parameter settings for Yumeshiho for the *parameter – leaves per node.* There was no adjustment needed for Ayahikari.

Table 5.1 Adjusted parameter values for parameter – *leaves per node* (only for Yumeshiho)

	Default	Yumeshiho
Node no	Leaves per node	Leaves per node
0	1	1
2.5	1	0.6
6	6	0.6

After the model improvement, the fitness of simulated and observed data for grain yield, GPC, dry matter production and LAI were much improved including late sowing data for both Ayahikari (Figure 5.1) and Yumeshiho (Figure 5.2). Comparison of graphics before and after the model improvement shows that data points moved towards 1:1 line.

For Ayahikari, the significantly overestimated grain yield (400-500 g m^{-2}) of the latest sowing date of both years reduced to around 300 g m^{-2} and become closer to the observed data (around 150 g m^{-2}) (Fig 5.1, a and f). There was not much improvement in the GPC (Fig 5.1, b and g). The significantly overestimated dry matter production at flowering (648 and 570 g m^{-2}) and maturity (751 and 857 g m^{-2}) of 2014 and 2015 were reduced (380 and 323 and, 520 and 458 g m^{-2}) (Fig 5.1, c and h; d and i) to closer values of that of observed dry matter production which were 150 and 200 g m^{-2} at flowering and, around 250 g m^{-2} at maturity. Observed LAI at latest sowing dates of two years were 0.9 and 0.7 in 2014 and 2015. It was overestimated to 1.1 and 1.5 and, was reduced after the improvement to 0.5 and 0.3 (Fig 5.1, e and j) .

For Yumeshiho, the significantly overestimated grain yield (350-450 g m^{-2}) of the latest sowing date of both years reduced to around 250 g m^{-2} and become closer to the observed data (around 150 g m^{-2}) (Fig 5.2, k and p). There was not much improvement in the GPC (Fig 5.2, l and q). The significantly overestimated dry matter production at flowering (778 and 696 g m^{-2}) and maturity (900 and 763 g m^{-2}) of 2014 and 2015 were reduced (317 and 297 and, 435 and 431 g m^{-2}) (Fig 5.2, m and r; n and s) to closer values of that of observed dry matter production which were 250 and 300 g m^{-2} at flowering and, between 250-300 g m^{-2} at maturity respectively. Observed LAI at latest sowing dates of two years were 0.9 and 0.7 in 2014 and 2015. It was overestimated to 1.1 and 1.5 and, was reduced after the improvement to 0.5 and 0.3 (Fig 5.2, o and t).

The four indices for model validation showed that the overall model performance across sowing groups was greatly improved after the model improvement (Table 5.2). When the whole set of sowing time data was used, RMSE for grain yield was 121.5 and 113.1 g m^{-2} respectively for Ayahikari and Yumeshiho before the model improvement, but they were reduced to 79.9 and 69.0 g m^{-2} respectively after the model improvement. RMSE for GPC was 1.9 and 2.5% respectively for Ayahikari and Yumeshiho, but they were reduced to 1.8 and 2.4% respectively after the model improvement. Likewise, RMSE for the dry matter production at both flowering and maturity was also reduced. RMSE for LAI was reduced from 0.9 to 0.6 in Yumeshiho, but not so in Ayahikari. The relative value of RMSE to average, RRMSE also followed the similar patterns.

Modelling efficiency (ME) for grain yield improved from 0.20 to 0.65 for Ayahikari and from 0.11 to 0.67 for Yumeshiho, both to the acceptable range. ME for GPC also improved to a certain extent, but still, it was not acceptable, particularly in Yumeshiho. ME for LAI also improved but not to the extent to be accepted, particularly in Ymueshiho, again. ME for dry matter at flowering also increased insufficiently, but that in Ayahikari was almost in the acceptable range. That at maturity increased in Ayahikari and rather decreased in Yumeshiho, but it was anyhow acceptable for both cultivars

m value became closer to one in general due to the model improvement. As the exceptions, *m* value for GPC in Ayahikari and LAI in Yumeshiho slightly more deviated from one.

Considering the range of these model performance indices, especially RMSE and ME, the overall model performance was acceptable for both verities.

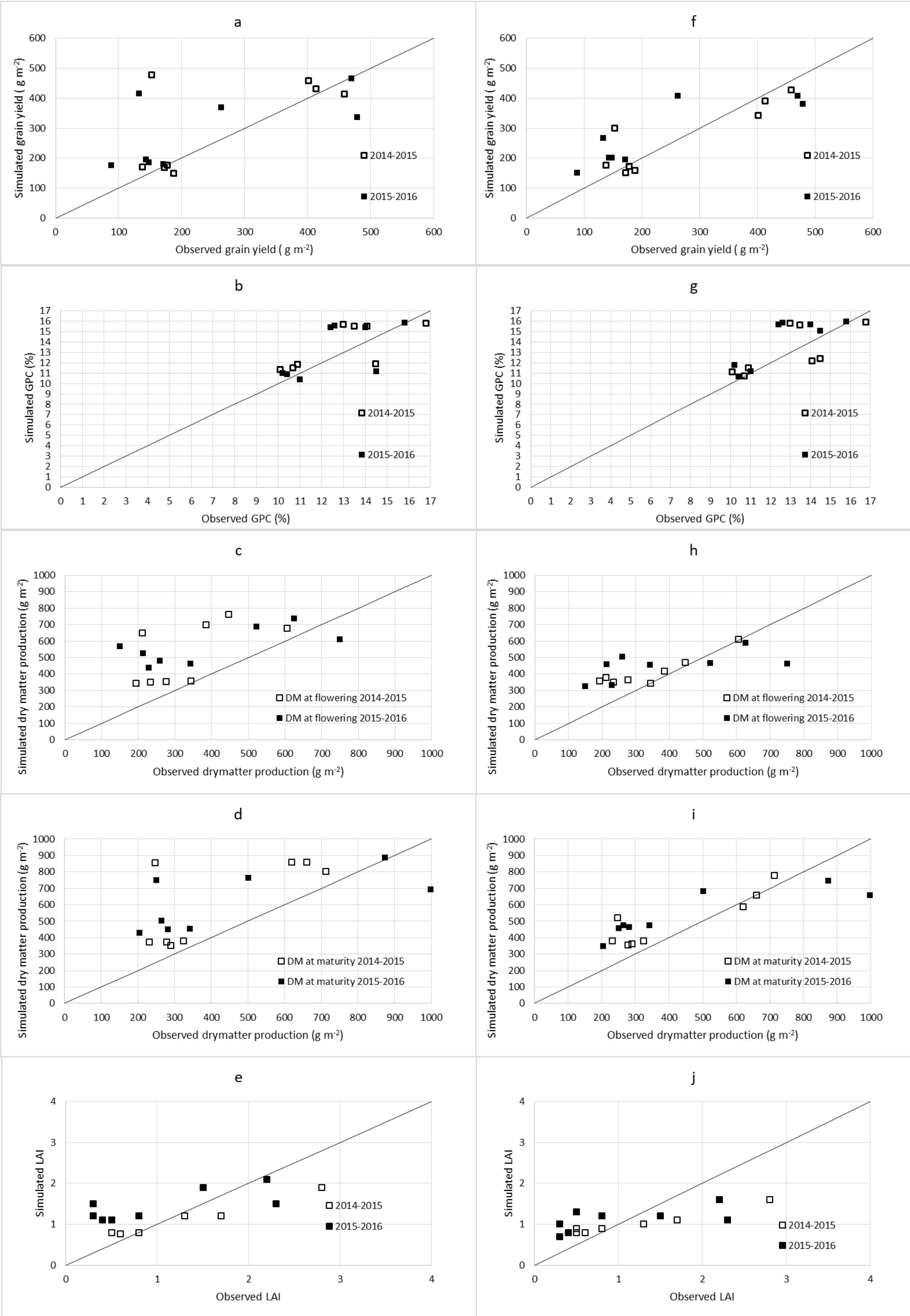

a
Simulated grain yield (g m-2)
Observed grain yield (g m-2)
2014-2015
2015-2016
f
Simulated grain yield (g m-2)
Observed grain yield (g m-2)
2014-2015
2015-2016
b
Simulated GPC (%)
Observed GPC (%)
2014-2015
2015-2016
g
Simulated GPC (%)
Observed GPC (%)
2014-2015
2015-2016
c
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at flowering 2014-2015
DM at flowering 2015-2016
h
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at flowering 2014-2015
DM at flowering 2015-2016
d
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at maturity 2014-2015
DM at maturity 2015-2016
i
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at maturity 2014-2015
DM at maturity 2015-2016
e
Simulated LAI
Observed LAI
2014-2015
2015-2016
j
Simulated LAI
Observed LAI
2014-2015
2015-2016

Figure 5.1 Simulated and observed grain yield, GPC and dry matter production at flowering and maturity, and LAI for Ayahikari, in 2014-2015, and 2015-2016 for all sowing groups before (a,b,c,d,e) and after (f,g,h,i,j) model improvement across all sowing groups. The black line is 1:1 line

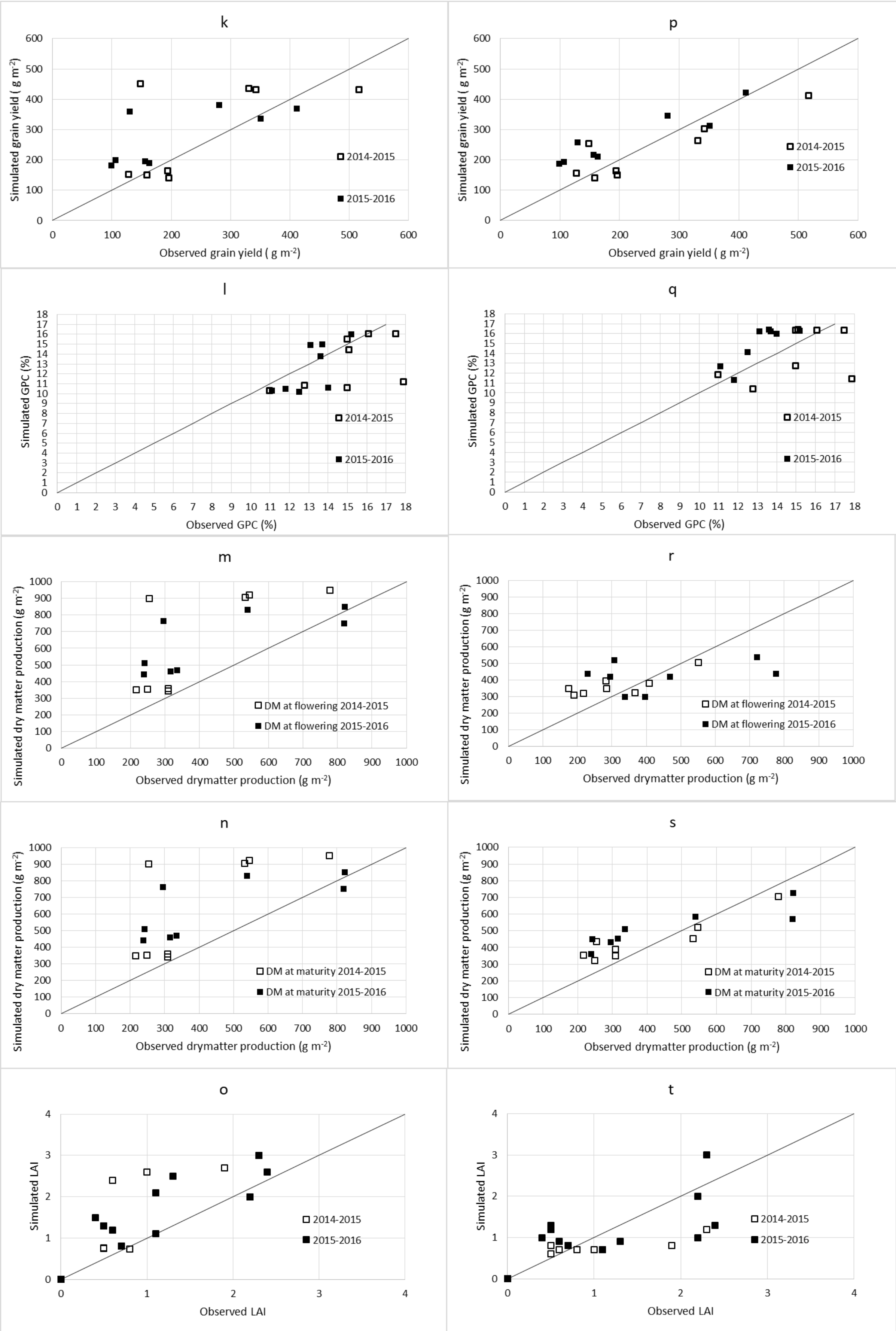

k
Simulated grain yield (g m-2)
Observed grain yield (g m-2)
2014-2015
2015-2016
p
Simulated grain yield (g m-2)
Observed grain yield (g m-2)
2014-2015
2015-2016
l
Simulated GPC (%)
Observed GPC (%)
2014-2015
2015-2016
q
Simulated GPC (%)
Observed GPC (%)
2014-2015
2015-2016
m
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at flowering 2014-2015
DM at flowering 2015-2016
r
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at flowering 2014-2015
DM at flowering 2015-2016
n
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at maturity 2014-2015
DM at maturity 2015-2016
s
Simulated dry matter production (g m-2)
Observed drymatter production (g m-2)
DM at maturity 2014-2015
DM at maturity 2015-2016
o
Simulated LAI
Observed LAI
2014-2015
2015-2016
t
Simulated LAI
Observed LAI
2014-2015
2015-2016

Figure 5.2 Simulated and observed grain yield, GPC and dry matter production at flowering and maturity, and LAI for Yumeshiho, in 2014-2015, and 2015-2016 for all sowing groups before (k,l,m,n,o) and after (p,q,r,s,t) model improvement across all sowing groups. The black line is 1:1 line

Table 5.2 Model performances before and after model improvement across all sowing groups (including early, optimum and late sowing)

Model attribute	Observed range	Model perfromance across all sowings before the model improvement				Model perfromance across all sowings after the model improvement			
		RMSE[a]	RRMSE[b]	ME[c]	*m*[d]	RMSE[a]	RRMSE[b]	ME[c]	*m*[d]
Ayahikari									
Grain yield (g m^{-2})	87- 478	121.5	48.6	0.20	1.05	79.9	32.0	0.65	0.96
GPC (%)	10.1-16.8	1.9	14.6	0.14	1.04	1.8	13.8	0.23	1.06
LAI	0.3-2.8	0.6	54.7	0.40	0.89	0.6	49.7	0.32	1.09
Drymatter at flowering (g m^{-2})	150-749	243.3	64.8	-0.81	1.31	141.7	39.2	0.45	0.99
drymatter at maturity (g m^{-2})	204-997	259.3	58.6	-0.12	1.18	160.1	36.1	0.57	0.98
Yumeshiho									
Grain yield (g m^{-2})	99-517	113.1	48.6	0.11	1.10	69.0	29.7	0.67	0.97
GPC (%)	11-17.9	2.5	17.4	-0.50	0.90	2.4	17.1	-0.46	1.01
LAI	0.4-2.4	0.9	76.7	-0.60	1.36	0.6	57.8	0.08	0.61
Drymatter at flowering (g m^{-2})	173-777	291.6	77.6	-1.87	1.50	146.3	38.9	0.27	0.90
drymatter at maturity (g m^{-2})	216-821	276.1	64.9	0.70	1.34	131.8	31.0	0.60	0.99

[a] Root mean square error

[b] Relative root mean square error

[c] Model efficiency

[d] Slope (m) of a best-fit regression line forced through the origin

5.4 Discussion

5.4.1 Validation across the sowing groups was success

It was shown in this chapter that the model improvement made the simulation output much closer to the observed data for the entire sowing dates tested including the sowing in late December(Figures 5.1 and 5.2). The degree of fitness of the model was evidently increased for the case of grain yield and dry matter at maturity, and the dry matter at flowering to the lesser extent. For GPC, although the RRMSE was relatively small, it did not further decrease owing to the model improvement. For LAI, the RRMSE was relatively high, but it decreased by the model improvement to a certain extent.

From these results, it can be concluded that the inclusion of the algorism of reducing the plant density when the emergence was delayed at the late sowing conditions was successful. And now the APSIM model can be used to for the simulation of both hard and soft winter wheat in Kanto region, and in other regions of the similar soil and climatic conditions even under late sowing conditions. This expansion on the applicability of the model is useful because in Kanto region farmers from time to time face that situation that they have to sow late due to autumn rains. To the author's knowledge, this is the first report of improving the APSIM model by integrating an empirical model to correct the plant density at emergence due to the low temperature at emergence.

5.4.2 Model validation results compared with the existing literature to show the acceptance of the validation

After the validation across all sowing groups, RMSE for grain yield was 79.9 and 69.0 g m^{-2} for Ayahikari and Yumeshiho, respectively. These RMSE values are within in the range of RMSE for grain yield reported in the literature (40 to 85, Asseng et al., 1998; Asseng et al., 2000; Chen et al., 2010 and Balwinder-Sing et al., 2011). As for the GPC, RMSE for Ayahikari and Yumeshiho were 1.8 and 2.4 % respectively which was within the range of the reported values in other studies (1.5 – 3.2 %, Asseng et al., 1998; Asseng et al., 2000; Asseng et al., 2002).

The ME values related to the grain yield were 0.65 and 0.67 for Ayahikari and Yumeshiho respectively which were within the range of that was reported by Chen et al. 2010 and Ahmed et al. 2016. (0.4-0.95). ME values between 0 and 1 are generally viewed as acceptable levels of performance and model performance can be evaluated as satisfactory, if ME > 0.50, good if ME > 0.65 and, very good if ME > 0.75 (Moriasi et al., 2007). Conversely, model validation was not at the level of success with the ME values of GPC as 0.23 and -0.46 for Ayahikari and Yumeshiho respectively. However, there has been no previous reports discussing the ME value for the GPC validation of APSIM model, while RMSE was reported to a certain extent (Asseng et al., 1998; Asseng et al., 2000; Asseng et al., 2002).

In APSIM there is no cultivar specific parameters directly related to the GPC. GPC is determined as the result of the balance of the inflow of carbon and nitrogen to the grains during the grain formation period, and thus the simulation accuracy tends to be lower compared with the dry matter production and yield. Still there should be the room of further improvement of model accuracy by conducting GPC specific calibration. In fact I found that the lower ME of GPC was caused by the overestimation at N160 treatment in Oct 23 and 13 Nov sowing groups in 2015 for Ayahikari, and the overestimation at N160 treatment in Dec 4 sowing group in 2015 for Yumeshiho. ME values was improved to 0.56 (Ayahikari) and 0.68 (Yumeshiho) when the above mentioned data points were excluded from the calculation.

5.4.3 Model development approach compared with the literature

It is not only in Japan, but also farmers from some other wheat producing countries as well have been facing the problem of reducing the wheat yields as they are compelled to sow late due to weather and field conditions. Late planting is a major limitation to wheat productivity in many regions of South Asia that have a rice-wheat cropping system (Hobbs et al., 1994). In Pakistan, areas with a rice-wheat cropping system, the wheat sowing is primarily delayed because of late harvest coupled with poor soil structure and loose plant residues, which adversely affects the preparation of the land for wheat cropping (Byerlee et al., 1984). Also, the occurrence of rains during the land-preparation period causes a further delay in sowing in Panjab in India and Pakistan (Aslam et al., 1993, as cited in Farroq et al., 2008).

However, the model improvement to increase the accuracy under late sowing conditions has not been done so far in APSIM (Bangyou Zheng personal communication from the APSIM develoment team member). The parameterization and validation of the APSIM wheat model was conducted exclusively for the optimal sowing to the author's knowledge (Asseng et al., 1998, 2000; Wang et al., 2013, Bai & Tao, 2017). While CERES and some other crop growth models have the "winter kill" function, the climatic conditions where this function was applied is different from the conditions of milder low temperature of this research.

In addition to the model improvement on planting density, I parameterized the number of leaves per node (*leaves_per_node*) parameter to improve the grain yield prediction under late sowing for the hard wheat variety, Yumeshiho. Unlike the plant density parameter (*density*) defined as an input parameter, *leaves_per_node* is set by an x-y function in APSIM wheat module (wheat.xml). Therefore, model improvement of this part is more complicated. And although the observed data of number of leaves per node or plant and the tiller number per plant regularly taken during the entire growth period is needed to derive any function to express this parameter, but such measurement was not undertaken in the current experiments. Therefore additional improvement on the *leaves_per_node* would be the remaining research opportunity for the future which may increase the model precision to simulate the decreased yield under the late sowing conditions of winter wheat.

5.4.4 Recommendations for farmers

According to the observed results from Chapter 3 and simulation results in this chapter, it was shown that the low temperature affected planting density was about one-fourth of the original one. Therefore, it can be suggested that the farmers would be able to compensate the yield losses under late sowing conditions by increasing the sowing density. An additional sensitivity analysis was conducted by increasing the sowing density (by 10, 30, 50, 90, and 100%) for Dec 24 latest sowing in 2014-2015 experiment. The results showed that by increasing the sowing density by 90%, the grain yield was increased (from 252/298 to 408/415; Yumeshiho/Ayahikari respectively) and become comparable to the one under optimal sowing date (410/426). The simulated plant number per area also increased (from 67/56 to 128/106) and approached to that of the optimal sowing (90/74). Studies from elsewhere had also reported that increasing sowing density resulted in higher grain yield under late sowing conditions (Spink et al., 2000; Baloch et al., 2010; McKenzie et al., 2007 and Nazir et al., 2000). McKenzie et al., (2007) reported that grain yield of late sown crop increased by on average 5 kg per kg increase in seeding rate.

5.4.5 Research needs for the validation and extension of the model to adjust the emergence percentage under low temperature conditions

In this chapter, I presented the methodology and the results for the acceptable validation and the improvement of the APSIM model for Kanto region across optimal and late sowing conditions. The empirical equation that explains the relationship between emergence percentage and number of dates to the emergence was developed based only on the field experiment of the two seasons with one soil type at single location. Therefore, it is suggested that the similar field experiments focused on the emerged plant density and plant production under the low temperature conditions should be conducted for other soil and climatic conditions, especially in the area and farming systems for which the late sowing is the real concern. It is needed to assess to what extent the constants in the aforementioned equation should be modified, or if there is need to modify the equation itself.

5.5 Conclusions

It can be concluded that, after the model improvement, APSIM model can be used for the simulation of both hard and soft winter wheat in Kanto region or in other regions under the similar soil and climatic conditions under the optimal and late sowing conditions.

Chapter 6

Scenario analysis for economically optimum nitrogen management for Kanto region, Japan

6.1 Introduction

Japanese farmers are subsidized for wheat production through “quality bonus” depending on the grain quality such as grain protein content (GPC). The highest quality bonus is offered for the hard and soft wheat with the grain protein range of 11.5 - 14% and 9.7 – 11.3% (ranking A), respectively (MAFF, 2014). Therefore, farmers can obtain dual benefits if they attain higher grain yield with expected GPC. GPC can be controlled by N management, but it is also affected by soil, climatic and various management factors. Therefore, decision support for the producers is indispensable to employ best nitrogen management to attain higher yield and required a range of GPC. The validated crop simulations models can be used for such tasks with long-term weather data to test numerous N management scenarios to obtain optimum N management regime.

The parameterization and validation of APSIM model was conducted for the wheat production in Kanto area in Japan in Chapter 4, and the model improvement for the late sowing conditions was done in Chapter 5. In this chapter, therefore, the validated model was applied to elucidate the economic management optima for N management.

An economic analysis was conducted followed by the simulation experiment to elucidate N management optima and both benefits from yield and GPC quality bonus were considered for the economic analysis.

As indicated in the chapter one (Table 1.1), there are three level of quality bonus rankings (A, B and C). So far ranking A was considered for the evaluation of hard and soft wheat performances (Chapter 2). Nevertheless, for the economic analysis and evaluating the N management optima, I considered the all three levels of quality bonus rankings in this chapter.

6.2 Materials and methods

6.2.1 Simulation experiment for obtaining optimum nitrogen management

A simulation experiment was conducted to find out the optimum nitrogen application rate and timing of application using the validated APSIM model configurations for both hard wheat (Yumeshiho) and soft wheat (Ayahikari) varieties. For the weather data, daily weather data (maximum and minimum temperature, precipitation and solar radiation) of past 55 years (1961 - 2016) was obtained at the Tokyo District Meteorological Observatory (N35°41.4', E139°45.6') (Japan Meteorological Agency http://www.data.jma.go.jp/obd/stats/etrn/index.php).

Validated APSIM model (Version 7.5) was used to run the simulations. Sixty four N application treatments, comprised of the full combinations of 4 levels of N rate at 3 timings, i.e., basal, stem elongation (DC 30-31) and 50% flowering (DC 65-68) were tested. The N rates for each timing was 0, 40, 80, and 120 kg N ha^{-1}. The simulation experiment was conducted for Yumeshiho (hard wheat) and Ayahikari (soft wheat) varieties, both. Growth stages are described as in Zadoks decimal code scale (DC) (Zadoks et al., 1974). A pre simulation was also conducted to identify the date of stem elongation and flowering for the fertilizer application using Nov 14 and No 13 sowing experimental data of 2014-2016 experiments.

The simulation was run for the period from 1961/10/01 to 2016/07/28. Date of sowing was fixed to Nov 13 and sowing density is 80 kg ha^{-1} (226 and 240 plants per m^2 for Ayhikari and Yumshiho, respectively) representing farmers practice in the region. Sowing depth was 2.5 cm, and row spacing was 19 cm. Soil water, Organic matter, and nitrogen were reset every year on October 1 to ensure that they remain stable over the simulation period. Altogether 7040 simulations were conducted (55 years x 64 N scenarios x two varieties).

6.2.2 Economic optima for the nitrogen application

Simulated grain yield and GPC were adjusted to the standard moisture contents; gain yield to 12.5% and GPC to 13.5% moisture percentage respectively before the economic analysis.

Economic analysis was conducted for all 64 treatments of N applications to find out the gross margin (ha^{-1}) with respect to the respective N treatment. The calculation of the gross margin was conducted using Excel spreadsheet based on the procedure described by Takahashi & Okada, (2013). First, the total revenue (ha^{-1}) was calculated as a sum of the revenue received for grain yield, quality bonus for GPC and, Acreage subsidy (universal payment). For the calculation of quality bonus, quality bonus ranking A and C was considered for the simplicity. If the GPC is within the range of ranking A, maximum quality bonus added or the quality bonus of rank C added otherwise (Table 6.1). However, for the evaluation of the results, all quality bonus ranking levels (A, B and C) were taken in to the account. Detailed information on the GPC ranges in each ranking of quality bonus and amount of quality bonus offered for hard and soft wheat is indicated in the Table 1.1 of the chapter one.

Then, total cost was calculated as a sum of fertilizer cost, other operational cost and, capital stock payment. Table 6.1 indicate the values of each parameter used for the calculation. Finally gross margin (ha^{-1}) was calculated as the difference of the total revenue and the total cost.

The gross margin was calculated from simulated grain yield and GPC for each year, and then the average was calculated for the 55 years. The economically optimum N application rate is the one which gives the highest averaged gross margin (among all 64 N treatments).

In addition to the 64 N treatments, an additional simulations were conducted for farmers' N application in the region and gross margin was calculated for both varieties, respectively.

Table 6.1 Parameters used for calculation

Parameter	Value	Source
Revenue		
Portion of wheat price unrelated to the quality (JPY t^{-1})	58,340	MAFF (2012)
Quality bonus for GPC (JPY t^{-1})		
Hard wheat	150,000 ($11.5<p<14$) or 118,833 (otherwise)	MAFF (2012)
Soft whet	107,500 ($9.7<p<11.3$) or 76,333 (otherwise)	
Acreage subsidy (JPY ha^{-1})	200,000	MAFF (2012)
Cost		
Fertilizer (JPY kg^{-1})	380	Retail price (2016)
Other operational cost (JPY ha^{-1})	377,760	MAFF (2012)
Capital stock payment (JPY ha^{-1})	115,220	MAFF (2012)

6.2 Results

The simulated grain yield, GPC and gross margin under the different N treatment scenarios (N1-N64) are shown in Figures 6.1 and 6.2 for Yumeshiho and Ayahikari, respectively, using box plot to visualize variation caused by the weather for 55 years. The height of the box presents the 25-to-75 percentile, whiskers (i.e., the horizontal dashes linked to boxes by vertical lines) present the 10-to-90 percentile, and the black line in the box is the median.

The median grain yield of Yumeshiho increased significantly from the lowest basal N application (0 kg N ha^{-1}) to the highest (120 kg N ha^{-1}) (Figure 6.1a). And the pattern of the grain yield increase caused by the split N application was somewhat similar for each basal N application level. Within each basal N level, grain yield increased when the N application at stem elongation increased up to 80 kg N ha^{-1} but very little between 80 to 120 kg N ha^{-1}. Grain yield response to the N application at flowering (the continuous 4 treatments within each stem elongation N treatment) was observed only at the 0 and 40 kg N ha^{-1} stem elongation application levels. At 80 and 120 kg N ha^{-1} stem elongation application levels, grain yield increase was much less irrespective of the amount of N applied at flowering. In general, the more contribution to the increase of grain yield came from the basal N application followed by the N application at stem elongation but less from N application at flowering.

The variation shown in the box plot at each N treatment is due to the year to year variation of for 55 years, which was higher at higher grain yield levels.

The median GPC of Yumeshiho increased significantly when the N application at flowering increased from 0 to 80 kg N ha^{-1} mainly within the 0 kg N ha^{-1} N level of stem elongation (Figure 6.1b). In general GPC increased when the N application at stem elongation increased from 0 to 40 kg N ha^{-1} and became more stable thereafter. The pattern of the GPC increase was similar for each basal N application level.

The gross margin of Yumeshiho followed the same pattern as grain yield (Figure 6.1c). At 0 and 40 kg N ha^{-1} N at stem elongation, gross margin increased when N application at flowering increased. However, at 80 and 120 N ha^{-1} N at stem elongation, where the yield was relatively stable, gross margin tended to decrease at higher N rate at flowering probably due to the increased cost. Variation of gross margin was higher at higher N application levels.

For Ayahikari, the pattern of the changes of grain yield, GPC and gross margin was similar to that of Yumeshiho in general (Figure 6.2). However the levels of highest median grain yield and GPC were lower than those of Yumeshiho (Figures 6.2a and c). Moreover, the variation of GPC (height of the box) of Ayahikari at the higher N levels was slightly wider than that of Yumeshiho (Figure 6.2b). The highest median gross margin of Ayahikari was lower than that of Yumeshiho even though the pattern was similar (Figure 6.2c). Similar to Yumeshiho, gross margin increased with increasing N application at flowering only at the lower N rate at stem elongation. The variation of gross margin of Ayahikari was wider than that of Yumeshiho especially at 80 and 120 kg N ha^{-1} basal N rates.

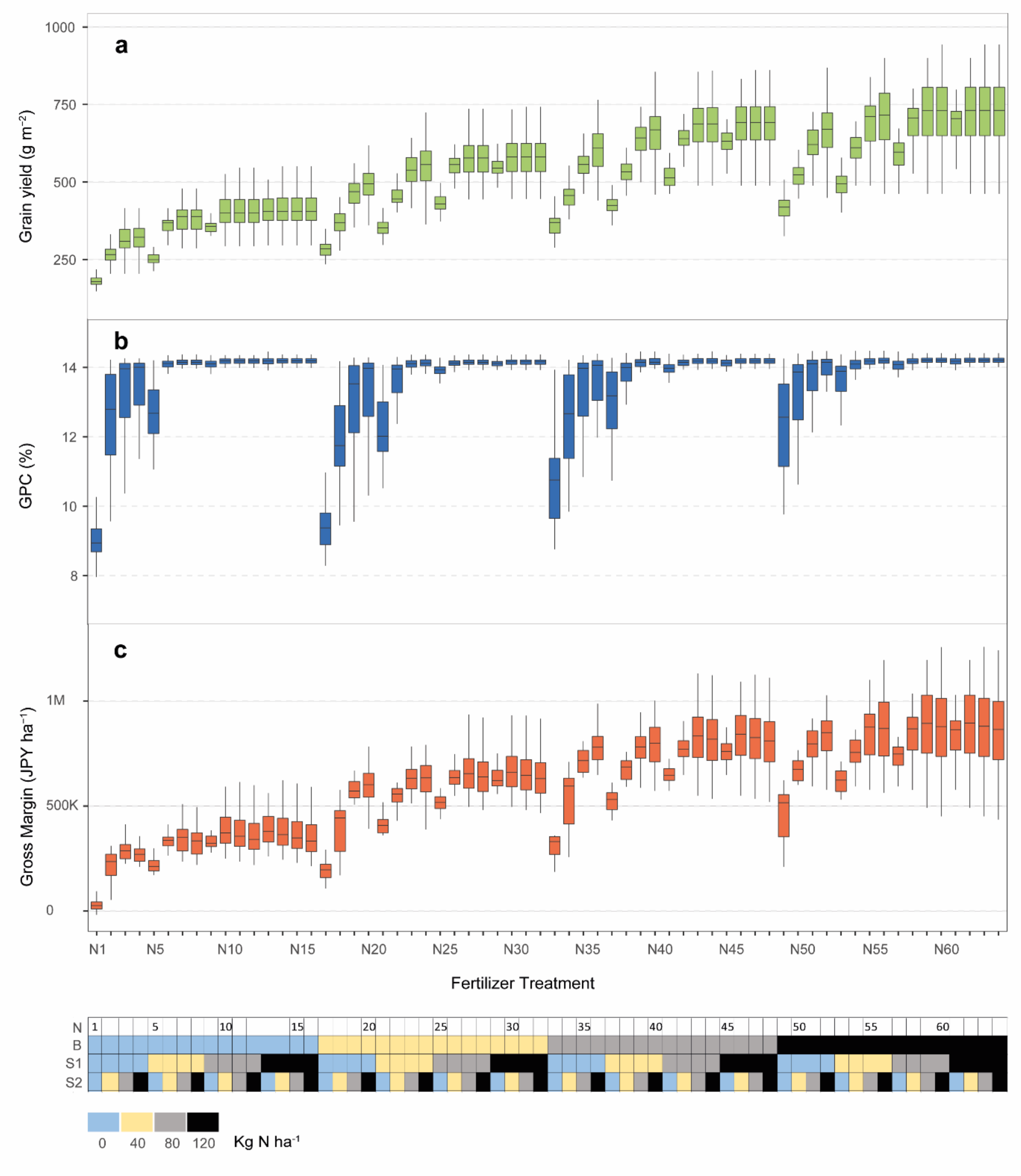


Figure 6.1 Variation of grain yield (a), GPC (b) and gross margin (c) of each N treatment for Yumeshiho. The patch chart below the figure indicates treatment number (N: 1-64), and the amount of N applied (with four colours) as basal (B), at stem elongation stage (S1), and at flowering (S2). For each box, the height of the box presents the 25-to-75 percentile, whiskers (i.e., the horizontal dashes linked to boxes by vertical lines) present the 10-to-90 percentile, and the black line in the box is the median.

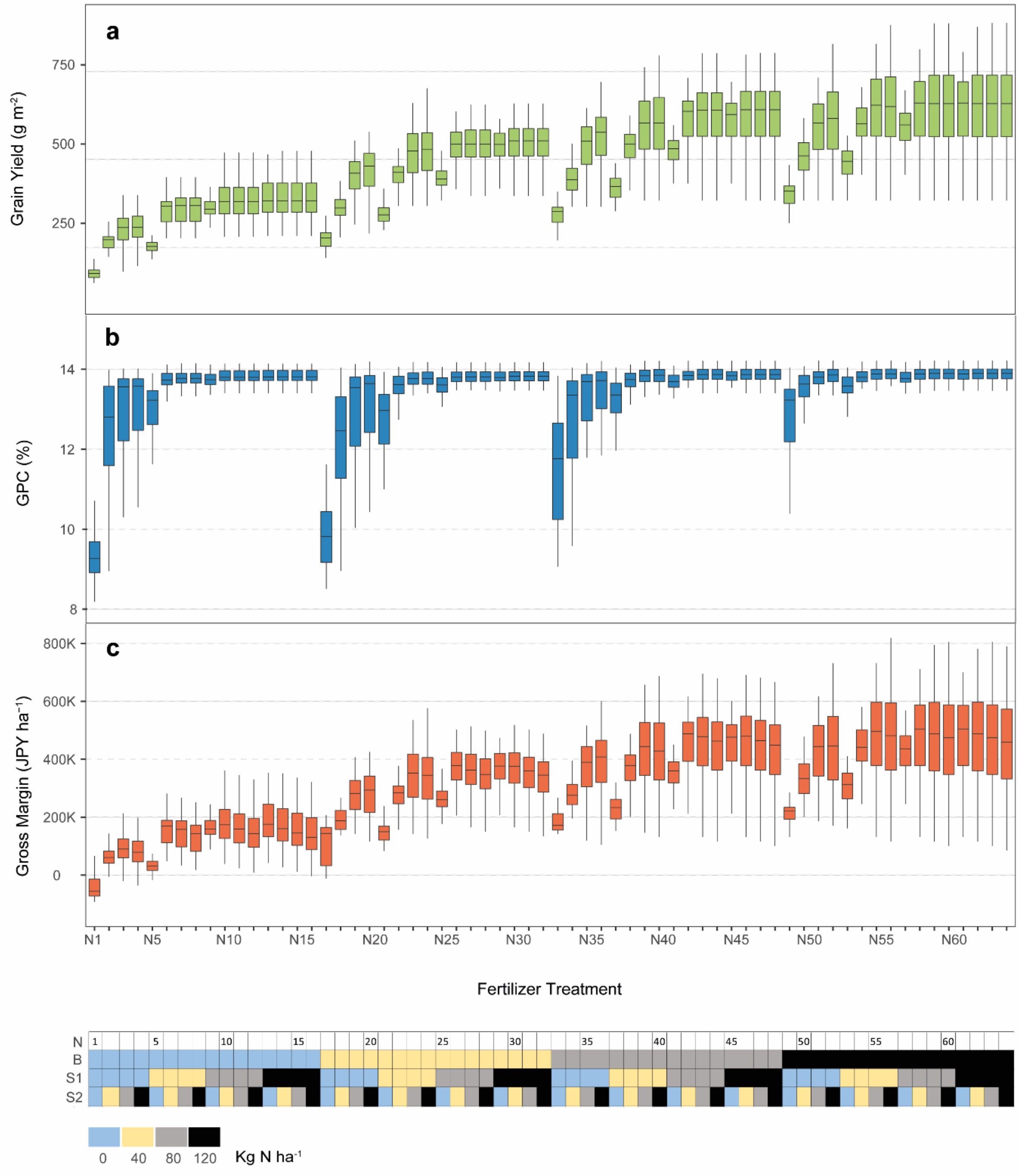


Figure 6.2 Variation of grain yield (a), GPC (b) and gross margin under (c) each N treatment (N1-N64) for Ayahikari. The patch chart below the figure with four colours shows the amount of N applied as basal (B), at stem elongation stage (S1), and at flowering (S2) under each N treatment. The boxes present the 25-to-75 percentile, whiskers (i.e., the horizontal dashes linked to boxes by vertical lines) present the 10-to-90 percentile, the black line in the boxes is median

The simulated grain yield, GPC and gross margin (average of 55 years) were plotted against the total amount of N applied ranging from 0 to 360 kg N ha^{-1} (Figure 6.3) The different data points represent each N treatment (N1-N64). Therefore, the variation within each total N amount was due to the different proportions of N application as basal, at stem elongation and at flowering.

When the highest grain yield of Yumeshiho under each total N level was considered, the grain yield became relatively stable at the total N rate higher than 280 kg N ha^{-1} (Figure 6.3 a). GPC of Yumeshiho increased up to 80 kg N $ha^{-1}$of total N and became stable thereafter. The highest average gross margin was 890,118 JPY ha^{-1} at N59 of 280 kg N ha^{-1} total N (120/80/80 for basal, at stem elongation stage and at flowering)

In case of Ayahikari also, the highest grain yield under each total N application level was increased up to 280 kg N ha^{-1} of total N level and then became relatively stable (Figure 6.3b). Similar to Yumeshiho, GPC of Ayahikari also increased up to 80 kg N $ha^{-1}$of total N level and became stable thereafter. The highest gross margin, 479,109 JPY ha^{-1} was observed at N62 (120/120/40), which was lower than that of Yumeshiho.

Therefore, it was elucidated that the economically optimum total N application rate was 280 kg N ha^{-1} for both hard and soft wheat, but the proportion of split application was different as mentioned above.

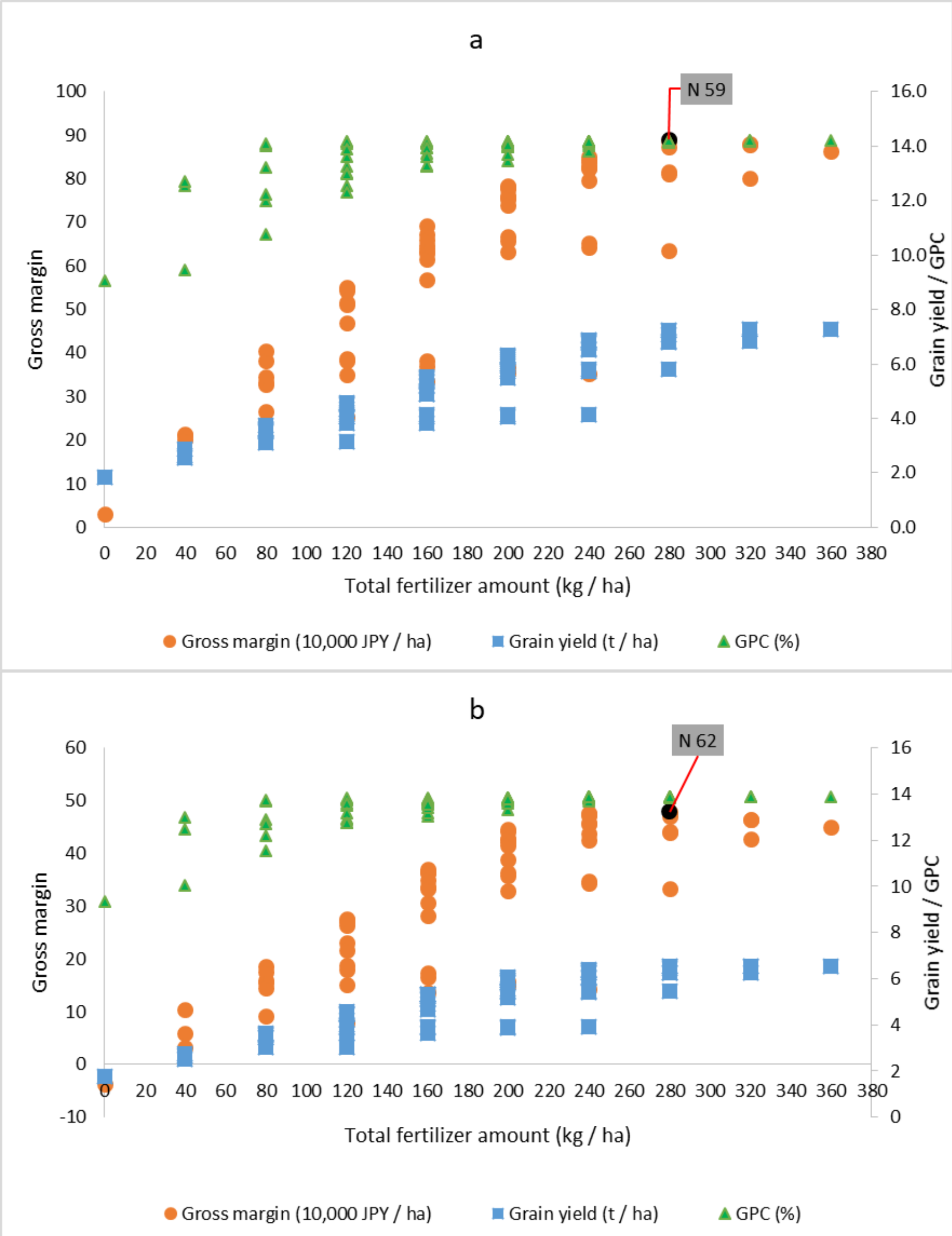


Figure 6.3 Variation of grain yield, GPC and gross margin with the amount of N applied. Primary Y-axis is gross margin (10,000* JPY ha^{-1}) secondary Y-axis is grain yield (t ha^{-1}), and GPC (%) and X-axis is the amount of N applied (0 – 360 kg ha^{-1}). Plot “a” denotes Yumeshiho and plot “b” denotes Ayahikari. (grain yield, GPC and, gross margin values are average of 55 years under each N treatment (N1-N64))

Table 6.2 is the summary of the fertilizer application guideline for wheat in the prefectures of central and southern part of Kanto region, where the weather is similar to the site of the present research. In Saitama and Chiba prefectures total application rate of 100 and 120 kg N ha^{-1} are recommended for drill sowing and broadcasting respectively. Of 120 kg N ha^{-1}, 80 kg N ha^{-1} is applied as basal and the rest is recommended to be applied in late February to early March. No N application is recommended at flowering stage. In Ibaraki and Kanagawa prefectures, and Tokyo Metropolis, the total fertilizer rate is from 50 to 80 kg N ha^{-1} which is even lower than that of Saitama and Chiba. Based on these fertilizer guidelines, total 100 kg N ha^{-1} was selected as the typical current farmers' practice around the research site, and then, additional simulations were conducted to compare the yield and other parameters under the elucidated most profitable N application scheme in this research and under the current farmers' practice.

Table 6.2 Fertilizer application guidelines for wheat in Kanto region

Prefecture	Varitey	Sowing method	Soil	Land use	Fertilizer scheme (kg/ha) Total	Basal	Split1	Timing of Split1	Split2	Timing of Split2	Ref.
Saitama	Ayahikari	Broadcast	-----	Converted from paddy	**120**	100	20	Late Feb.	0		1
	Ayahikari	Drill	-----	Converted from paddy	**100**	80	20	Late Feb.	0		1
	Ayahikari	-----	Alluvial	-----	**100-120**	40	40	Early to mid March	20-40	Heading	
Chiba	-----	Drill	-----	Upland	**100**	80	20	Early March	0		2
	-----	Broadcast	-----	Upland	**120**	100	20	Early March	0		2
	-----	Drill	-----	Converted from paddy	**100**	80	20	Early March	0		2
	-----	Broadcast	-----	Converted from paddy	**120**	100	20	Early March	0		2
Ibaraki	Norin61, Kinunonami, Satonosora	Drill	Black volcanic ash soil	Converted from paddy	**70**	60	10	Late_Feb～Early March	0		3
	Norin61, Kinunonami, Satonosora	Drill	Alluvial	Converted from paddy	**80**	60	20	Late_Feb～Early March	0		3
	Norin61, Kinunonami, Satonosora	Drill	Black volcanic ash soil	Upland	**60**	60	0	Late_Feb～Early March	0		3
	Norin61, Kinunonami, Satonosora	Drill	Alluvial	Upland	**80**	60	20	Late_Feb～Early March	0		3
Tokyo	-----	-----	Black volcanic ash soil	Upland	**50**	30	20	-----	0		4
	-----	-----	Alluvial	Upland	**60**	40	20	-----	0		4
Kanagawa	Norin61	Row	Volcanic ash	Upland	**70**	40	30	Mid March	0		5
	Norin61	Row	Alluvial	Upland	**65**	45	20	Mid March	0		5
	Norin61	Drill	Alluvial	Upland	**70**	50	20	Mid March	0		5
	Norin61	Broadcast	Alluvial	Upland	**70**	50	20	Mid March	0		5

'---- : no mention

1. Guidelines for fertilizer application for major crops (March 2013), Saitama Prefecture
2. Guidelines for fertilizer application for major crops (March 2009), Chiba Prefecture
3. Guidelines for fertilizer application for major crops (March 2010), Ibaraki Prefecture
4. Guidelines for fertilizer application for major crops (unknown), Tokyo Prefecture
5. Guidelines for fertilizer application for major crops (March 2013) Kanagawa, Prefecture

According to the simulation results, the median yield at farmers' N application scheme was 382 and 393 g m^{-2} for both Ayahikari and Yumeshiho respectively (Figures 6.4a and 6.4b). Whereas, the median grain yield at optimum N treatment was 660 and 730 g m^{-2} for Ayahikari and Yumeshiho, respectively, or 72.7 and 85.7 % higher than those at the farmers' N treatment. Median grain yield at maximum N treatment was similar to that of optimal N scheme for both varieties.

Median GPC was 12.9 % in Ayahikari and 12 % in Yumeshiho at the farmers' practice (Figures 6.4c and 6.4d). The former exceeded the ranges of both A and B quality bonus windows of soft wheat, while the latter was within rank A quality bonus window of hard wheat. At the optimal N treatment, GPC of Ayahikari again exceeded the both quality bonus windows, and that of Yumeshiho was within rank B quality bonus window. Median GPC at maximum N treatment was similar to that of the optimal N treatment in both varieties.

Median gross margin was 199,279 and 483,569 JPY ha^{-1} for Ayahikari and Yumeshiho respectively, at the farmers' N application scheme (Figures 6.4e and 6.4f). However, median gross margins at optimum N scheme was 489,512 and 893,965 JPY ha^{-1} for Ayahikari and Yumeshiho respectively, which is 145.6 % higher in Ayahikari and 84.8 % higher in Yumeshiho compared to that at the farmers' N application scheme. Since neither yield nor GPC advantage increased at maximum N scheme compared to that at the optimum scheme, the gross margin rather tended to decrease owing to the increased cost of fertilizer.

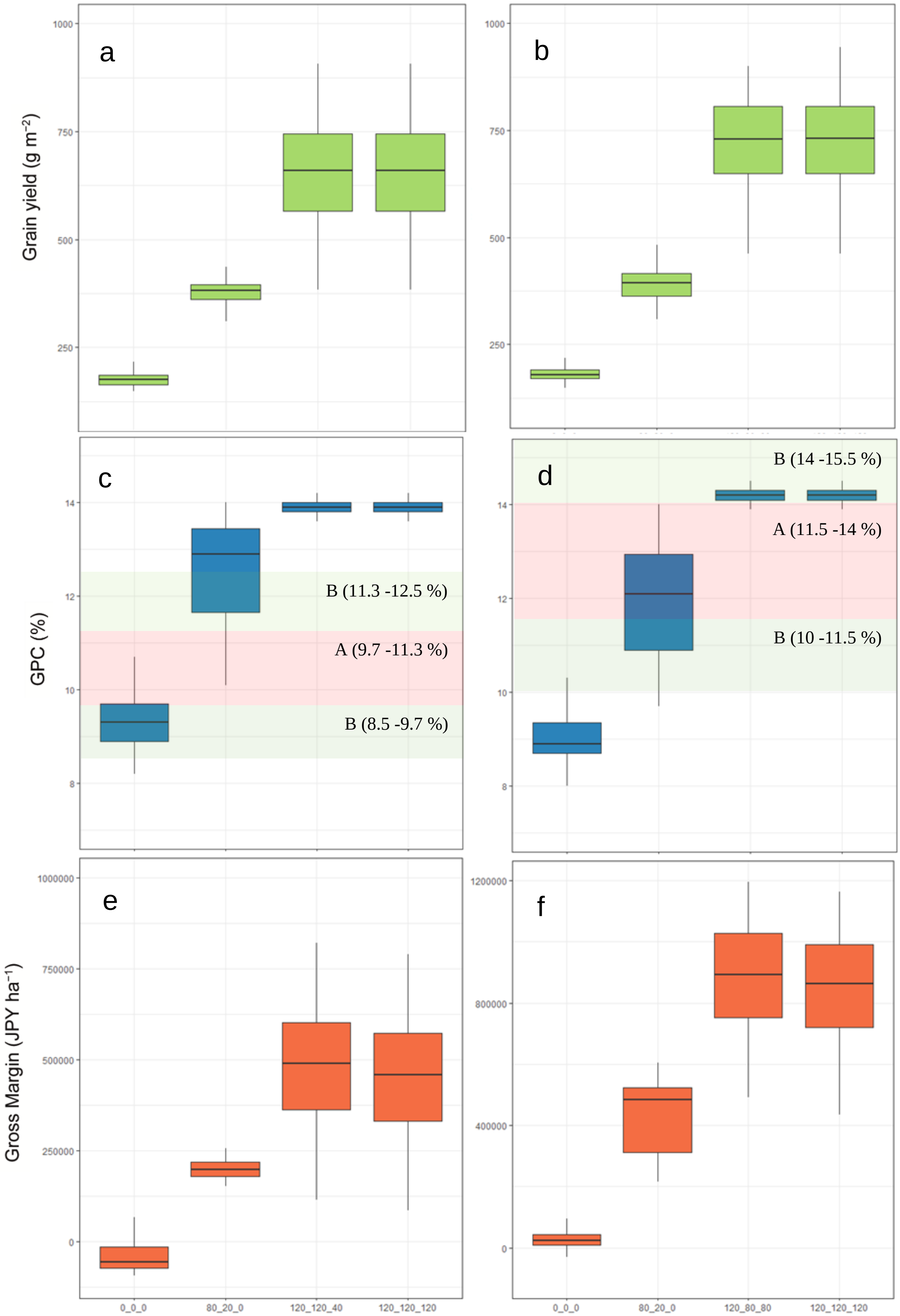

a
b
c
d
e
f
Grain yield (g m⁻²)
GPC (%)
Gross Margin (JPY ha⁻¹)
B (11.3 -12.5 %)
A (9.7 -11.3 %)
B (8.5 -9.7 %)
B (14 -15.5 %)
A (11.5 -14 %)
B (10 -11.5 %)
0_0_0
80_20_0
120_120_40
120_120_120
120_80_80

Figure 6.4 Variation of grain yield, GPC and, gross margin at the lowest (0_0_0), farmers' practice (80_20_0), optimum (280; 120_120_40 / 120_80_80) and, maximum (120_120_120) N levels for Ayahikari and Yumeshiho. Plot "a,c and e" denotes Ayahikari and plot "b,d and f" denotes Yumeshiho. Shaded areas in graph c and d denote the quality bonus windows. Pink denotes the rank A quality bonus and green denotes rank B quality bonus. The boxes present the 25-to-75 percentile, whiskers (i.e., the horizontal dashes linked to boxes by vertical lines) present the 10-to-90 percentile, the black line in the boxes is median.

So far the economically optimum N treatment was determined based on the gross margin averaged for the 55 years. However, from another point of view, economically optimum N treatment can be determined for each year by comparing the gross margin of different treatments and therefore, optimum N treatment is expected to vary from year to year. Figure 6.5 shows such changes of optimal N treatment of each year over the 55 years, together with the changes of grain yield, GPC and gross margin. Change in average annual temperature (AAT) and precipitation (AAP) is also plotted for comparison. During 55 years both AAT and AAP showed an increasing trend. However the variability of the AAP among the years were very high. The increasing trend was significant only for AAT ($y = 0.0287x - 40.872$, $P<0.001$).

The most profitable N treatment (optimum) of each year for Yumeshiho was relatively stable and stayed slightly higher than N60 until around the year 1990 and then tended to be lower (Figure 6.5a). This results was close to the most profitable N scheme (optimum) elucidated above, i.e., N59 (120/80/80, total 280 kgNha^{-1}). In fact, the total N rate of the most profitable treatment was from 240 to 280 kg N ha^{-1} in 31 years, more than half of the 55 years of the simulation. However, the N treatment number became sporadically very low for some years (e.g. 1980, 1984) which is accompanied with the downward spikes of yield and gross margin. The total N rate for these years were 160-200 kg N ha^{-1}, slightly lower than that of the normal years. Out of 55 years, GPC of was within the rank A quality bonus window for 23 years in the case of Yumeshiho.

The optimal N treatment of each year for Ayahikari also tended to stay at around N62 (120/120/40, total N rate was 280 kg N ha^{-1}) until 1990, but then started to fluctuate and tended to be lower thereafter (Figure 6.5b). In fact, N62 was identified as the optimum N treatment for 16 years among 55 years of the simulation period, and the total N rate was 240 to 280 kg N ha^{-1} for 34 years within 55 years. Similar to the case of Yumeshiho, the grain yield and gross margin generally followed the same pattern of the number of the N treatment. Out of 55 years, GPC at the economically optimum N treatment was higher than the upper limit of rank A quality bonus window for most of the years except only for 7 years.

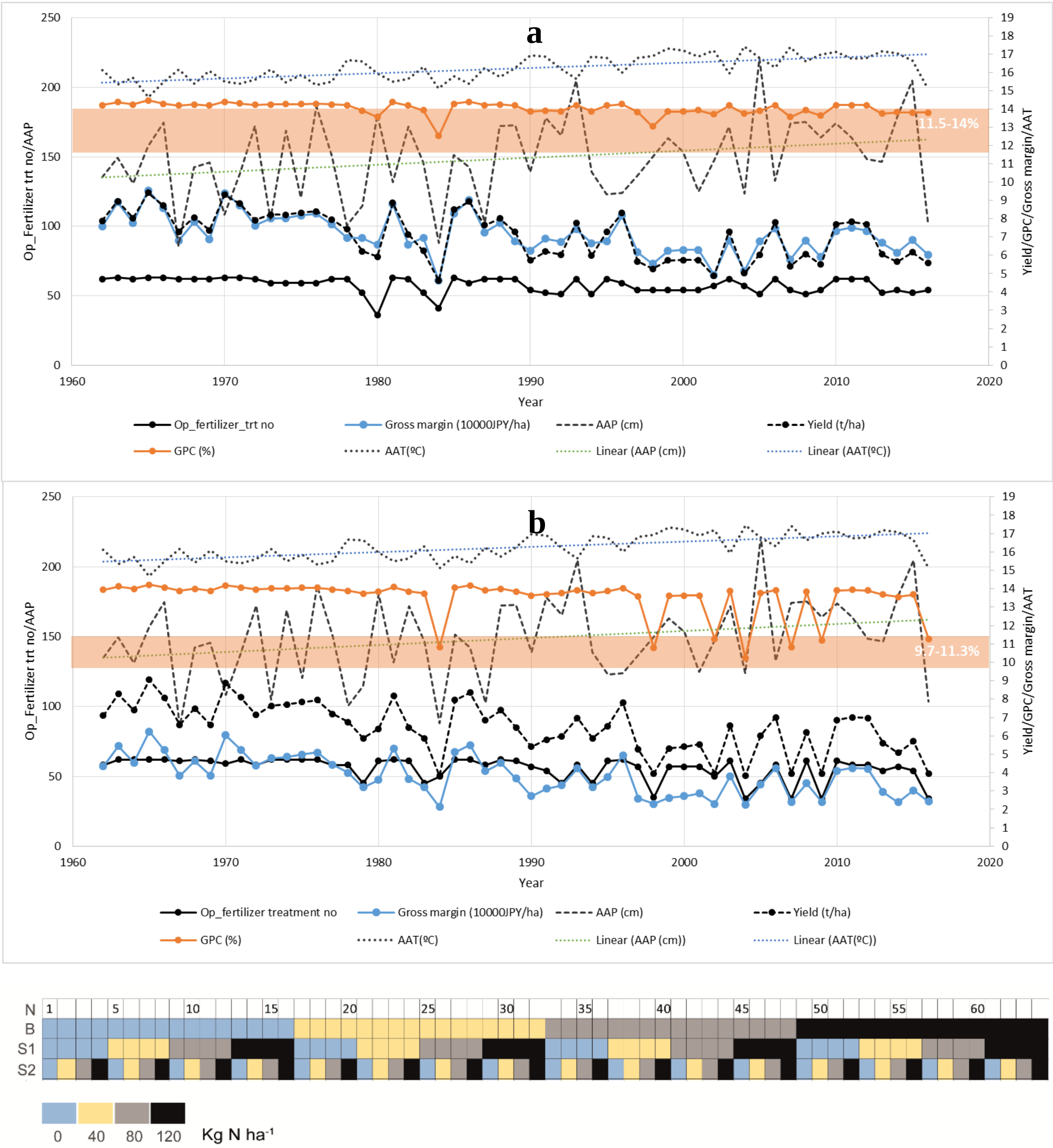


Figure 6.5 Change in optimal N application rate over the 55 years and respective grain yields, GPCs and gross margins of Yumeshiho (a) and Ayahikari (b). Change in annual average temperature (AAT) and precipitation (AAP) is also indicated. Shaded area in orange is the rank A quality bonus window for both varieties. The patch chart below the figure with four colours shows the amount of N applied as basal (B), at stem elongation stage (S1), and at flowering (S2) under each N treatment.

6.3 Discussion

The purpose of this scenario analysis was to find out the economically optimum N application scheme by testing the wider range of N treatments with different combinations of basal and split applications. This would provide guidance to increase profitability of the wheat farmers in Kanto area in Japan by increasing yield and obtaining the benefits of quality bonus. Fifty five years' historical daily weather data was used to test the effect of long-term climate variability on the effectiveness of each scenario.

The economically optimum N application rate derived from simulated results was 280 kg N ha^{-1} in total for both hard and soft wheat varieties. Although the total N amount was similar, split N rates were different for both varieties: 120/80/80 for hard wheat, and 120/120/40 for soft wheat (kg N ha^{-1} for basal, split at stem elongation stage and at flowering stage). With this optimum N application scheme, farmers can obtain maximum gross margin of 890,118 JPY for hard wheat and 479,109 JPY ha^{-1} for soft wheat.

In the real world, the recommended fertilizer level in the mid to southern Kanto area corresponding to the present study is from 50 to 120 kg ha^{-1} as the total application rate (Table 6.2). And the average wheat yield in the corresponding prefectures was 2.9, 4.0 and 3.2 t ha^{-1} for Ibaraki, Saitama and Chiba, respectively in 2017 (no data was available for Tokyo and Kanagawa) (MAFF, 2017). If the fertilization scheme of 80/20/0 (kg N ha^{-1} as basal, at stem elongation stage, and at flowering) is chosen as the typical of the region, the simulated yield was 3.9 and 3.8 t ha^{-1} for Yumeshiho and Ayahikari, respectively (the average between the yield levels of 80-0-0 and 80-40-0). These simulated yield level is, therefore, comparable to the yield level of the statistics of the prefectures. In contrast to these fertilizer scheme of current level, the scenario analysis suggested the possibility of attaining much higher yields and gross margins at the higher fertilization levels with higher proportion at the later stages of the growth.

The lower wheat yield in Japan compared to that in typical wheat growing countries in Europe has been the concern for many years as was discussed in the Introduction (Chapter 1.1). Recently National Agricultural Research Organization (NARO) of Japan compared the wheat growing conditions among those European countries, New Zealand and Japan, and found a large difference in the N fertilizer scheme (Watanabe, 2014 and Watanabe et al., 2016). In New Zealand and Europe generally, much lower rate of N fertilizers were applied as basal (adjusted by soil N test) and much higher rate up to 200 kg N ha^{-1} is applied as split application at later stages. Then the researchers at NARO hypothesized that the general lower wheat yield in Japan is due to the lower total N rate with higher proportion for basal application (typically 80 and 20 kg N ha^{-1} for basal and split application as was discusses above), and the yield can be increased by increasing the total N rate with higher proportion at stem elongation stage. To test this hypothesis Watanabe et al. (2016) tested higher N application rate (190 kg N ha^{-1} in total) with higher dose of split application at stem elongation stage (90 kg N ha^{-1}). The resulted grain yield was 6 – 6.6 t ha^{-1}, while the N rate around the conventional level (130 kg N ha^{-1}) resulted closer to the Japanese average level (4.3 – 4.6 t ha^{-1}). Fujita et al. (2015) also reported that grain yield increased up to 10 t ha^{-1} when the total N application rate was increased to 220-290 kg N ha^{-1} with higher dose at later split application (80 kg N ha^{-1}). Matsuyama et al. (2016) reported that the application of total 270 kg N ha^{-1} with 3 times split application of each 80 kg N ha^{-1} at later stages (stem elongation, jointing and flag leaf) for Ayahikari resulted in 7.6-7.8 t ha^{-1} grain yield with 13.6-13.2 % of GPC.

The optimal N rate derived from the simulation analysis of this research suggested the advantage of increasing the rate of total N application up to 280 kg N ha^{-1}. At the optimal N treatment, yield of Yumeshiho and Ayahikari increased up to 7.2 and 6.6 t ha^{-1} respectively which is within the range of what was reported in field experiments as discussed above. The respective GPCs were 14.2 and 13.9 % for Yumeshiho and Ayahikari. As a negative effect of increasing N application rates to very high levels, Watanabe et al. (2016) reported some lodging. The basal application of 120 kg N ha^{-1} recommended by current scenario analysis also might give some risk of lodging. However, the use of 120 kg N ha^{-1} rate as basal application did not cause any lodging in our field experiment in 2014-2016 for both hard and soft wheat (Chapter 2).

The highest gross margin of Yumeshiho (hard wheat) obtained at optimum N scheme was higher than that of Ayahikari (soft wheat) owing to the higher quality bonus for hard wheat compared with that of soft wheat. Under optimum N rates, both Yumeshiho and Ayahikari resulted in higher grain yield. However, GPC belonged to the rank B quality bonus range for hard wheat (14 – 15.5 %) and rank C quality bonus range for soft wheat (> 12.5 %) which gave a 5.8 % and 28 % less quality bonus compared to the premium quality bonus (rank A) respectively for hard and soft wheat. As reported in Chapter 2, higher indigenous N supply capacity of volcanic ash soils in Kanto region might have increased the GPC content excessively. Therefore, the current scenario analysis of different N fertilization scheme suggest that the producers might be able to maximize the benefit more by pursuing the higher grain yield through higher N application, rather than suppressing the N rate trying to obtain the quality bonus by controlling the GPC. However, the strategy would be different where the indigenous N supply capacity is lower and there is a possibility to attain the target GPC by moderately increasing the N rate compared to the current level.

The simulation results showed that yearly optimal N application scheme tend to change to some extent due to year to year climate variation during the 55 years period in both varieties. However during the average years it was at or closer to the optimal N scheme derived based on the average gross margin of 55 years (280 kg N ha^{-1}). It was indicated that yearly optimal N scheme tended to be at lower N application rates in the years of unfavorable climate. For example, the lowest grain yield for Ayahikari was observed in 1984 and 2004 in which optimum N application rate was the second lowest (160 kg N ha^{-1}; 120/0/40) and the lowest (120 kg N ha^{-1} ; 80/0/40), respectively. Further, the results suggested that in unfavorable year, it is better to target the benefits from quality bonus to maximize the gross margin rather focusing on grain yield. This study showed that hard wheat production is more profitable than soft wheat, because the hard wheat producers can receive benefit from both grain yield and GPC quality bonus. Elucidated N rates were based on the economic point of views. Therefore, it is suggested to conduct further analysis to evaluate the environmental impact of this higher optimum N rates in order to provide further insight about the sustainability of the system.

Thus, results from the simulation study helped to evaluate the wheat farming system for N application, and thereby providing important information to improve the productivity for better economy of the producers. Therefore, use of validated crop model is very useful to provide necessary decision support to the farmers. Literature elsewhere also reported similar studies, i.e. simulation studies for wheat cultivation with the use of APSIM crop model for evaluating wheat production systems with different perspectives. Asseng et al. (2000) derived N management optima for wheat in Netherland using simulation analysis with validated APSIM model. The optimal N rate they derived was 270 kg N ha^{-1} which resulted in 8.5 t ha^{-1} of yield and 14 % GPC for winter wheat and there results were demonstrated to be in consistence with the results of field experiment. Liu et al. (2016) conducted a simulation study to encounter the soil organic C change in wheat cropping system in Australia with long-term climate variability in relation to different N application rates. Bai et al. (2016) evaluated the effect of modern fertilizer and other agronomic management practices to increase the yield in rice wheat rotation system in China during past 28 years mitigating effects of climate change. Luo et al. (2009) had studied the wheat grain yield response to changes in N application rate and in cultivar choice under dry and wet climatic conditions which will be expecting under future climate change in Australia. However, this is the first study of such simulation scenario analysis conducted to provide N management decision support to improve the wheat productivity in Japan.

6.4 Conclusions

The results of this simulation study indicated that economically optimum rate of total N application for both Yumeshiho (hard wheat) and Ayahikari (soft wheat) was 280 kg N ha^{-1}. Split N rates were, however, different: 120-80-80 kg N ha^{-1} for Yumeshiho, and 120-120-40 for Ayahikari (at sowing, at stem elongation stage and at flowering, respectively). With these optimum N treatments, the producers can obtain by 84.8 and 145.6 % higher median gross margin (one out of 2 year chance) compared to the current level for Yumeshiho and Ayahikari, respectively. Thus, the use of APSIM model for decision support on N management helped to elucidate optimum N application regimes for typical hard and soft wheat varieties grown in Kanto region, Japan using a broad range of N application rates even taking the long-term climate variation into account.

Chapter 7

APSIM model application to Hokkaido region: parameterization, validation and scenario analysis for economically optimum nitrogen management

7.1 Introduction

Hokkaido is the largest wheat producing region in Japan which accounts for 64.7% of the total national production. Tokachi plain, Toumon-Kitami region, Furano basin, and Ishikari plain are referred as the four wheat production centers and of which first three together named as the eastern field region and the forth named as the western paddy region (Nihei, 2012).

The total wheat production area in Hokkaido is about 120,000 ha, of which 90% produces the winter wheat. According to the statistics 75% of area is cultivated with a soft wheat variety named Kitahonami which is the major wheat cultivar grown at present followed by Yumechikara, a hard wheat cultivar. Yumechikara is cultivated in 9.5 % of the total area. Therefore, these are the two representative, leading wheat verities in the Hokkaido region at present.

In the previous chapter, I elucidated the N management optima for hard and soft wheat in Kanto region with a simulation study using APSIM crop model. In this chapter, firstly, I focused on the parameterization and validation of APSIM model for the major hard and soft wheat cultivars of Hokkaido region. Secondly, I conducted simulation study to elucidate the economically optimum N management optima for the Hokkaido region.

7.2 Materials and methods

7.2.1 Model calibration and validation

ASPIM model calibration and validation was conducted for Kitahonami and Yumechikara winter wheat varieties which are the mostly grown representative soft and hard wheat cultivars in Hokkaido.

APSIM model 7.5 was used throughout this chapter. Soil data for the Hokkaido were obtained from the soil grid (https://www.soilgrids.org) based on the geographical coordinates of the experimental locations (Kunneepu, Kitami and Sapporo) where the data of filed experimental were obtained. Soil water data were estimated using the soil texture data as described by Saxton and Rawls, (2006). Description of soil data is indicated in Table 7.2.

Daily weather data were obtained from the nearest weather station data of Japan Meteorological Agency. For Kitami, it was Kitami weather station (17.3 Km away from Kunneppu experimental location) and for Sapporo, it was Sapporo weather station (13 Km away from experimental location). Since the daily solar radiation data were not available for Sapporo, it was obtained from NASA power data (https://power.larc.nasa.gov/), based on the geographical coordinates.

Model calibration and validation was conducted using the published field experimental data and description about the data set is mentioned in Table 7.1. Calibration and validation procedure was as same as described in Chapter 4.

Table 7.1 Description of the experimental data used for model calibration and validation

Variety	Source of data	Area	Year of experiment	N application	Use of data
Kitahonami	Kasajima et al. 2016	Kitami, Hokkaido	1. 2011-2012, 2. 2012-2013	1 40/50/0 2. 40/50/50 (B/SE/FL)	Calibration
	Yamada et al. 2016	Kitami, Hokkaido	1. 2014-2015 2. 2015-2016	56/50 (B/FL)	Validation: phenology
	Araki 2016	Kitami, Hokkaido	2014-2015	60/20/40/40 (B/SE/PI/FL)	Validation: grain yield
	Sawaguchi et al. 2014	Kitami, Hokkaido	2011-2012 1. Sowing denisty 140 (Sep 14 and 21 sowing) 2. Sowing density 100 (Sep 21 sowing)	N1. 60/40/40/60 (B/Boot/PI/FL) N2. 60/80/60 (B/PI/FL)	Validation: grain yield
	Fueki et al. 2015a	Kitami, Hokkaido	1.2007-2008 2.2008-2009	N1: 40/80/40 (B/Boot/FL) N2: 40/80/40 (B/PI/FL)	Validation: GPC
Yumechikara	Tsuji et al. 2009	Sapporo, Hokkaido	2007-2008	40/90 (B/SM)	Calibration
	Tsuji et al. 2010	Sapporo, Hokkaido	2008-2009	N1: 40/0/0/0 (B/SM/PI/FL) N2: 40/90/0/0 (B/SM/PI/FL) N3: 40/90/30/0 (B/SM/PI/FL)	Validation: Phenology Grain yield GPC

Stage of fertilizer application: B - Basel, Boot-Booting, PI-Panicle initiation, FL-Flag leaf, SM-After snow melting

Table 7.2 Description of soil data

Area	Depth (mm)	Soil physical parameters			Volumetric water content (%) at		
		Sand (%)	Clay (%)	BD (g cm^{-3})	Permenent wilting point	Field capacity	Saturation
Kitami	0-5	0.40	0.21	1.20	0.13	0.27	0.42
(43º 45' N, 143º 43' E)	5-20	0.39	0.21	1.30	0.13	0.27	0.42
	20-50	0.41	0.20	1.40	0.13	0.26	0.41
	50-110	0.43	0.21	1.50	0.13	0.26	0.40
	110-210	0.45	0.22	1.50	0.13	0.26	0.40
Sapporo	0-5	0.42	0.17	0.70	0.11	0.24	0.40
(43º 0' N, 141º 24' E)	5-20	0.43	0.19	0.70	0.12	0.24	0.39
	20-50	0.43	0.20	0.70	0.12	0.25	0.39
	50-110	0.45	0.21	1.40	0.13	0.25	0.39
	110-210	0.45	0.22	1.50	0.13	0.25	0.40

7.2.2 Scenario analysis to derive N management optima

7.2.2.1 Simulation experiment for obtaining optimum nitrogen management

A simulation experiment was conducted to find out the optimum nitrogen application rate and timing of application using the validated APSIM model configurations for both hard wheat (Yumechikara) and soft wheat (Kitahonami) varieties for 30 years, with past 30 years daily weather data (1986-2016). Daily weather data was obtained from Kitami and Sapporo weather stations of Japan Meteorological Agency, for Kitahonami and Yumechikara respectively (7.2.1). Sowing date was Sep 20 which is in optimal sowing window of Hokkaido. Sowing rated used was 225 seed per m^2. Row spacing was 200 mm and sowing depth was 25 mm. The simulation experiment comprised of 64 different nitrogen application treatments which comprised of a basal and two split application at stem elongation stage (DC 30-31) and flowering stage (DC 65-68).

The fertilizer application rates and all experimental procedures are as same as described in 6.2.1 in Chapter 6. Altogether 3840 simulations were conducted (30 x 64 x 2). Grain yield, GPC were recorded for each year under each N scenario for each variety.

Simulated grain yield and GPC were adjusted to the standard moisture contents; gain yield to 12.5% and GPC to 13.5% moisture percentage respectively before the economic analysis.

7.2.2.2 Economic optima for the nitrogen application

The gross margin was calculated from simulated grain yield and GPC for each year, and then the average was calculated for the 30 years. The economically optimum N application rate is the one which gives the highest averaged gross margin (among all 64 N treatments).

In addition to the 64 N treatments, an additional simulations were conducted for farmers' N application in the region and gross margin was calculated for both varieties respectively.

Detailed procedure for calculating the gross margin is described in elsewhere of this thesis (6.2.2, Chapter 6).

7.3 Results

7.3.1 Model calibration and validation

Calibration of APSIM model for Kitahonami and Yumechikara was conducted with the experimental data from Kasajima et al. 2016 and Tsuji et al. 2009 (Table 7.1). Derived cultivar parameters for Kitahonami and Yumechikara are shown in Table 7.3. All parameters except maximum grin weight were derived with trial and error method. For the maximum grain weight, 1000 grain weights of two cultivars, mentioned in the experimental data were used.

Table 7.3 Cultivar parameter values obtained for both cultivars

a.

Phenology Parameters	Default value	Values	
		Kitahonami	Yumechikara
Sensitivity to vernalization	1.5	3.4	4.9
Sensitivity to photoperiod	3.0	1.0	2.3
Thermal time from emergence to end of juvenile stage (^{0}C d^{-1})	400	465	350
Thermal time from end of juwenile to floral initiation stage (^{0}C d^{-1})	555	544	555
Thermal time from beginning of grain filling to maturity (^{0}C d^{-1})	580	390	750

b.

Growth Parameters	Default value	Values	
		Kitahonami	Yumechikara
Maximum specific leaf area for delta LAI	27000-22000	27000-22000	22000-16000
Grains per gram stem	25	33	40
Maximum grain size	0.041	0.042	0.043
Potential grain filling rate	0.002	0.01	0.009

*1000 grain weight used as maximum grain size

After obtaining the cultivar parameters, validation of APSIM model for the phenology, grain yield and GPC of Kitahonami and Yumechikara was conducted with the experimental data. For Kitahonami, the number of days from sowing to flowering and maturity data from Yamada et al. (2016) was used for the validation of the phenology while the grain yield data from Araki (2016) and Sawaguchi et al. (2014) was used for the validation of grain yield. GPC data from Fueki et al. (2015) was used for the GPC validation.

Graphical comparison of simulated and observed phenology, grain yield and GPC of both varieties with 1:1 line is shown in Figure 7.1. It showed that the respective data points of number of days to flowering and maturity, grain yield and, GPC of both varieties were fitted close to 1:1 line showing that simulated data are fitted with that of observed.

Observed data set used for the validation were from the field experiments conducted with wider range of N application and different timing of application. It was between 100 and 200 kg N ha^{-1} for Kitahonami data set and between 40 and 160 kg N ha^{-1} for Yumechikara data set. The change in grain yield and GPC of Observed data was manifested in simulated data as well (Figure 7.2) which indicates that model could capture the response of two varieties to the amount of N applied and the timing of application. Furthermore, Sawaguchi et al. (2014) data set was comprised of two sowing times and sowing densities. Therefore, the grain yield validation of Kitahonami was included the effect of sowing densities and sowing times.

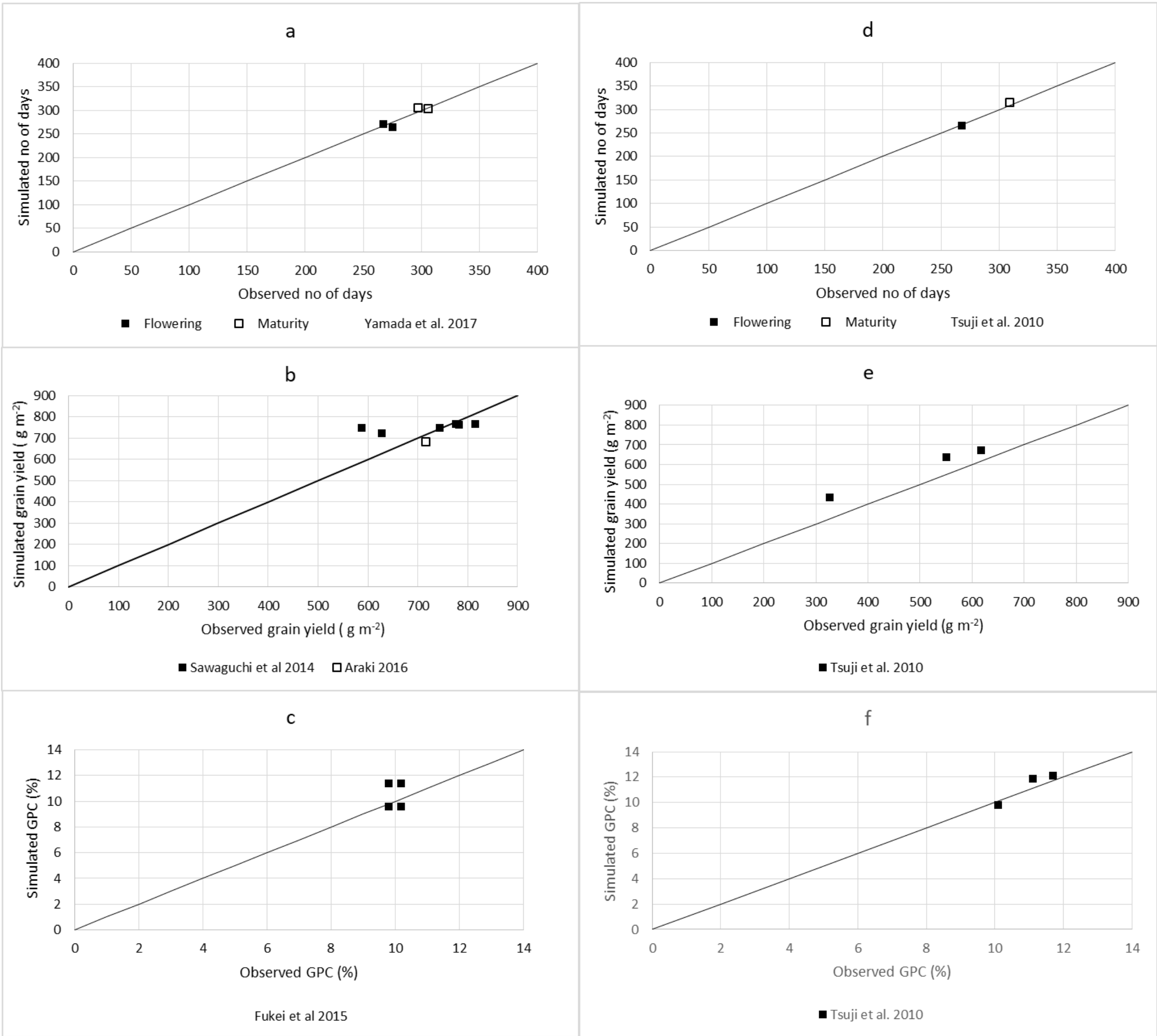
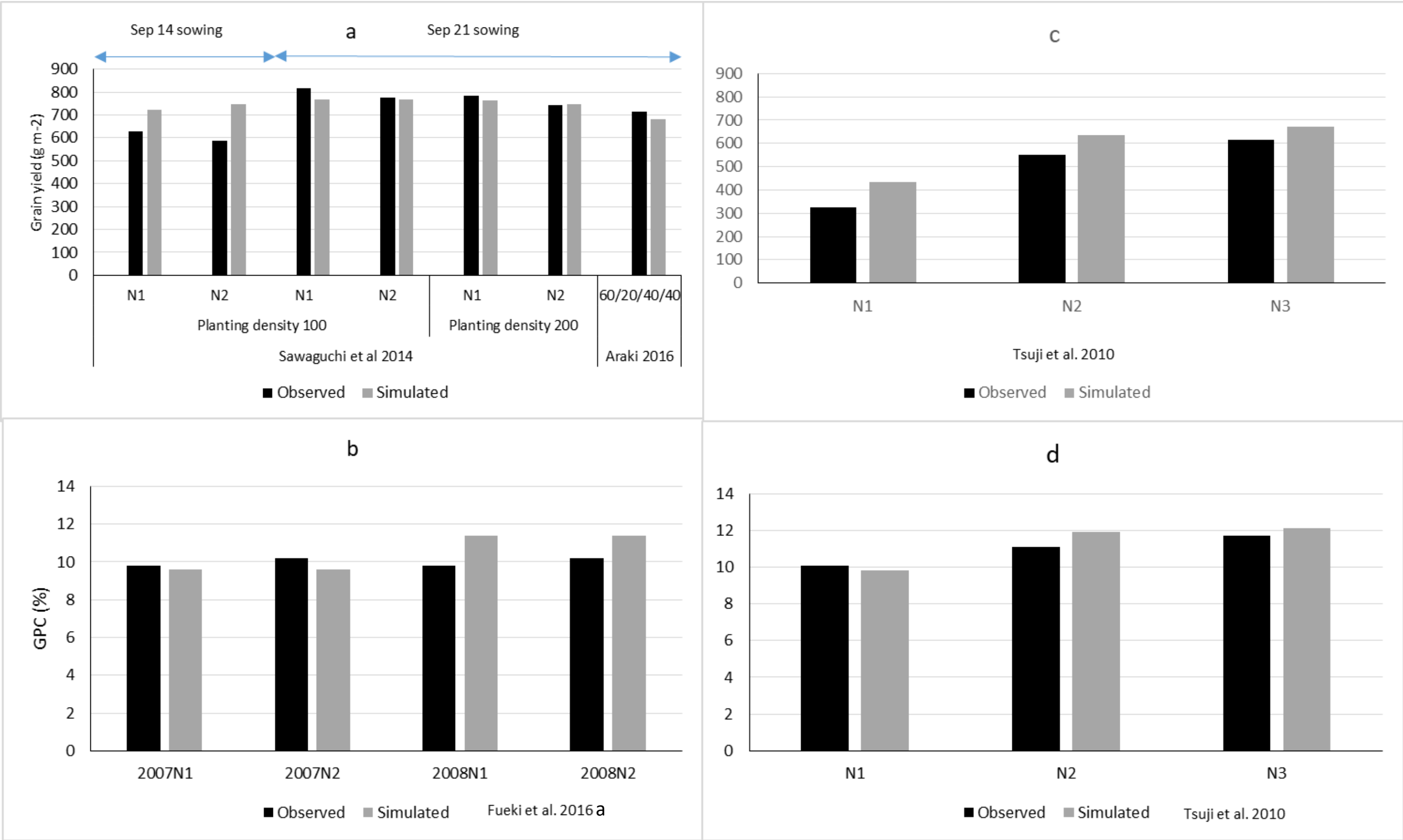


Figure 7.1 Simulated and the observed number of days to flowering and maturity, grain yield and GPC of Kitahonami (a-c) and Yumechikara (d-f).



Sawaguchi et al. 2014 (N1: 60/40/40/60 ; Basal/Booting/Panicle initiation/Flag leaf N2: 60/80/60; Basal/Panicle initiation/Flag leaf)

Araki 2016 (60/20/40/40; Basal/Stem elongation/Panicle initiation/Flowering)

Fueki et al. 2015 (N1:40/40/80; Basal/Flag leaf/Booting N2:40/40/80; Basal/Flag leaf/Panicle initiation)

Tsuji et al. 2010 (N1: 40; basal N2: 40/90; Basal/After snow melting N3: 40/90/30; Basal/After snow melting/Panicle initiation)

Figure 7.2 Simulated and the observed grain yield and GPC of Kitahonami (a-b) and Yumechikara (c-d) at different N application treatments.

The results of APSIM model performance for Kitahinami and Yumechikara evaluated based on statistical indices (RMSE, RRMSE, ME and, *m*) are shown in Table 7.4.

For Kitahonami, RMSE values were 6 days, 75 g m^{-2}, and 1% for phenology, grain yield and, GPC respectively. The respective RRMSE values were 2.1, 10.4, and 10.4% which were within <10 % range for phenology and within 10-20 % range for grain yield and GPC. Modelling efficiency (ME) values for phenology, grain yield and GPC were 0.88, 0.08 and, 0.98 respectively. *m* values for phenology, grain yield and GPC were 1.00, 0.94, and 1.04 respectively. According to the *m* value, grain yield simulation shows slightly underestimation and accordingly ME value was also lower compared to that of phenology and GPC.

For Yumechikara, RMSE values were 4 days, 86 g m^{-2}, and 0.5 % for phenology, grain yield and, GPC respectively. The respective RRMSE values were 1.2, 17.2, and 4.9 % which were within <10 % range for phenology and within 10-20 % range for grain yield and GPC. ME values for phenology, grain yield and GPC were 0.94, 0.5 and, 0.3 respectively. *m* values for phenology, grain yield and GPC were 1.00, 1.14, and 1.02 respectively. According to the *m* value, grain yield and GPC simulation shows slightly overestimation and accordingly ME values were also lower compared to that of phenology.

Table 7.4 Summary of APSIM model performances for Hokkaido region

Model attribute	Observed range	RMSE[a]	RRMSE[b]	ME[c]	*m* [d]
Kitahonami					
Phenology (days)	267-309	6.0	2.1	0.88	1.00
Grain yield (g m^{-2})	587-815	75.0	10.4	0.08	0.94
GPC (%)	9.8-10.2	1.0	10.4	0.98	1.04
Yumechikara					
Phenology (days)	265-315	4.0	1.6	0.94	1.00
Grain yield (g m^{-2})	327-617	86.0	17.2	0.50	1.14
GPC (%)	10.1-11.7	0.5	4.9	0.30	1.02

[a] Root mean square error

[b] Relative root mean square error

[c] Model efficiency

[d] Slope (m) of a best-fit regression line forced through the origin

7.3.2 Scenario analysis to derive N management optima

The simulated grain yield, GPC and gross margin under the different N treatment scenarios (N1-N64) are shown in Figure 7.3 and 7.4 for Kitahonami and Yumechikara, respectively, using the box plot to visualize variation caused by weather for 30 years. The height of the box presents the 25-to-75 percentile, whiskers (i.e., the horizontal dashes linked to boxes by vertical lines) present the 10-to-90 percentile, and the black line in the box is the median.

The median grain yield of Kitahonami increased significantly from the lowest basal N application level (0 kg N ha^{-1}) to the 40 kg N ha^{-1}. From 40 to 120 it increased but the increase was smaller than that of at 40 kg N ha^{-1}. (Figure 7.3 a). However the pattern of the grain yield increase was relatively same for each basal N application level. Within each basal N level (up to 80 kg N ha^{-1}), grain yield increased when the N application at stem elongation increased up to 80 kg N ha^{-1}. However, increase of grain yield from 0 to 40 kg N ha^{-1} is higher than that of 40 to 80 kg N ha^{-1}. Grain yield response to the N application at flowering (the continuous 4 treatments within each stem elongation N treatment) was observed only at the 0 and 40 kg N ha^{-1} stem elongation application levels. At 80 and 120 kg N ha^{-1} stem elongation application levels, grain yield increase was less irrespective of the amount of N applied at flowering. In general, the more contribution to the increase of grain yield came from the basal N application followed by the N application at stem elongation but less from N application at flowering.

The variation shown in the box plot at each N treatment is due to the year to year variation of weather for 30 years, which was higher at all grain yield levels.

The median GPC of Kitahonami increased significantly when the N application at flowering increased from 0 to 40 kg N ha^{-1} within the 0 kg N ha^{-1} N level at stem elongation (Figure 7.3 b). In general GPC increased when the N application at stem elongation increased from 0 to 40 kg N ha^{-1} and became more stable thereafter. The pattern of the GPC increase was same for each basal N application level. There was a higher year to year variation of the GPC at all N application levels.

The gross margin of Kitahonami followed the same pattern as grain yield (Figure 7.3 c). At 0 kg N ha^{-1} N application levels at stem elongation, gross margin increased when the N application at flowering increased up to 40 kg N ha^{-1} and decreased thereafter. On the other hand, gross margin increased with increased N application up to 40 kg N ha^{-1} at stem elongation within the 0 and 40 kg N ha^{-1} at basal application levels. Variation of the gross margin was very high at predominantly 80 and 120 kg N ha^{-1} basal application levels. This higher variation was observed at 50-75 percentile.

In general, the pattern of the changes of grain yield, GPC and gross margin of Yumechikara was similar to that of Kitahonami (Figure 7.4). However the levels of highest median grain yield and GPC were higher than those of Kitahonami. Particularly, increase of grain yield in response to 80 and 120 basal N application levels was higher than that of Kitahonami. Moreover, the variation of GPC (height of the box) of Yumechikara at the higher N levels was narrower than that of Kitahonami. The highest median gross margin of Yumechikara was higher than that of Kitahonami and the variation (height of the box) of the gross margin was lower than that of Kitahonami at higher N levels. Similar to Kitahonami, gross margin increased with increasing N application at stem elongation and decreased with N application at flowering.

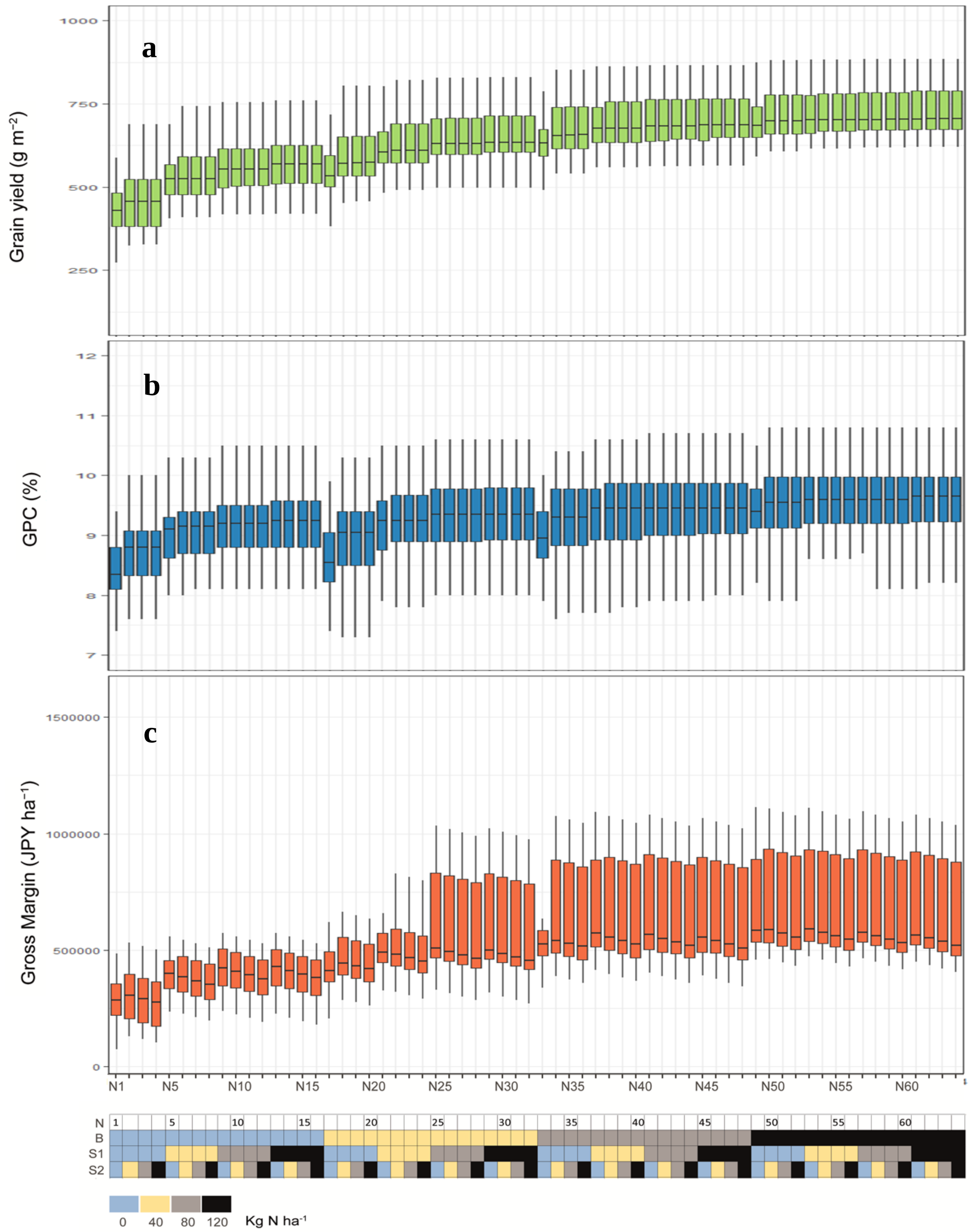

a
b
c
Grain yield (g m⁻²)
GPC (%)
Gross Margin (JPY ha⁻¹)
1000
750
500
250
12
11
10
9
8
7
1500000
1000000
500000
0
N1
N5
N10
N15
N20
N25
N30
N35
N40
N45
N50
N55
N60
N
B
S1
S2
0
40
80
120
Kg N ha⁻¹

Figure 7.3 Variation of grain yield (a), GPC (b) and gross margin (c) of each N treatment for Kitahonami. The patch chart below the figure indicates treatment number (N: 1-64), and the amount of N applied (with four colours) as basal (B), at stem elongation stage (S1), and at flowering (S2). For each box, the height of the box presents the 25-to-75 percentile, whiskers (i.e., the horizontal dashes linked to boxes by vertical lines) present the 10-to-90 percentile, and the black line in the box is the median.

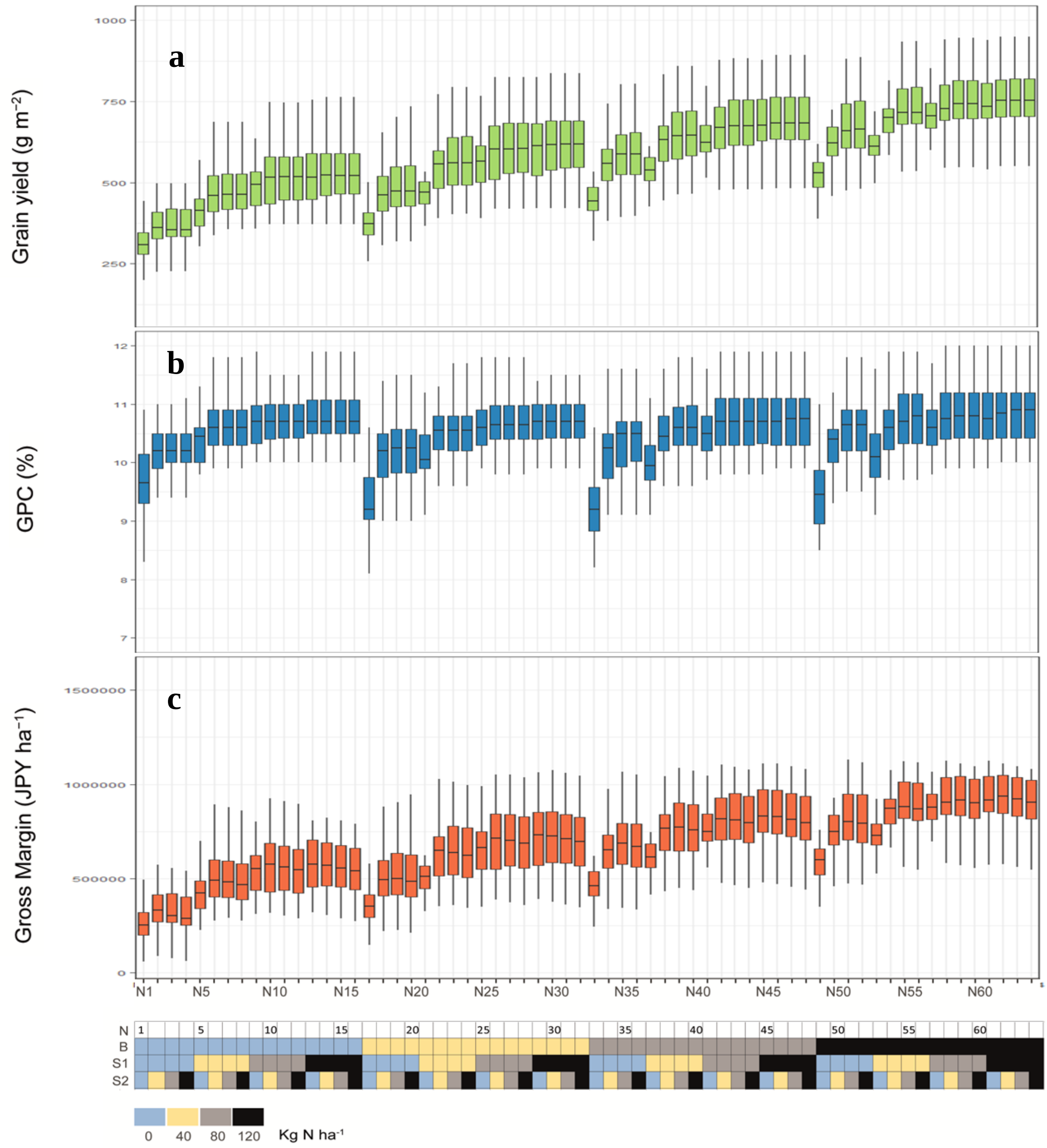


Figure 7.4 Variation of grain yield (a), GPC (b) and gross margin (c) of each N treatment for Yumechikara. The patch chart below the figure indicates treatment number (N: 1-64), and the amount of N applied (with four colours) as basal (B), at stem elongation stage (S1), and at flowering (S2). For each box, the height of the box presents the 25-to-75 percentile, whiskers (i.e., the horizontal dashes linked to boxes by vertical lines) present the 10-to-90 percentile, and the black line in the box is the median.

The simulated grain yield, GPC and gross margin (average of 30 years) were plotted against the total amount of N applied ranging from 0 to 360 kg N ha^{-1} (Figure 7.5) The different data points represent each N treatment (N1-N64). Therefore, the variation within each total N amount was due to the different proportions of N application as basal, at stem elongation and at flowering.

When the highest grain yield of Kitahonami under each total N level was considered, the grain yield became relatively stable at the total N rate higher than 160 kg N ha^{-1} (Figure 7.5 a). The GPC also increased up to 160 kg N $ha^{-1}$of total N and became stable thereafter. The highest average gross margins was 722,926 JPY ha^{-1} at N53 of 160 kg N ha^{-1} total N (120/40/0 for basal, at stem elongation stage and at flowering).

In case of Yumechikara, the highest grain yield under each total N application level was increased up to 280 kg N ha^{-1} of total N level and then became relatively stable (Figure 7.5b). Similar to Kitahonami, GPC of Yumechikara also increased up to 120 kg N $ha^{-1}$of total N level and became stable thereafter. The highest average gross margin, 984,515.8 JPY ha^{-1} was observed at N62 (280 kg N ha^{-1} in total split to 120/120/40 at basal, stem elongation stage, and at flowering, respectively) which was higher than that of Kitahonami.

Therefore, it was elucidated that the economically optimum total N application schemes were 160 kg N ha^{-1} (120/40/0) and 280 N ha^{-1} (120/120/40) for soft and hard wheat respectively.

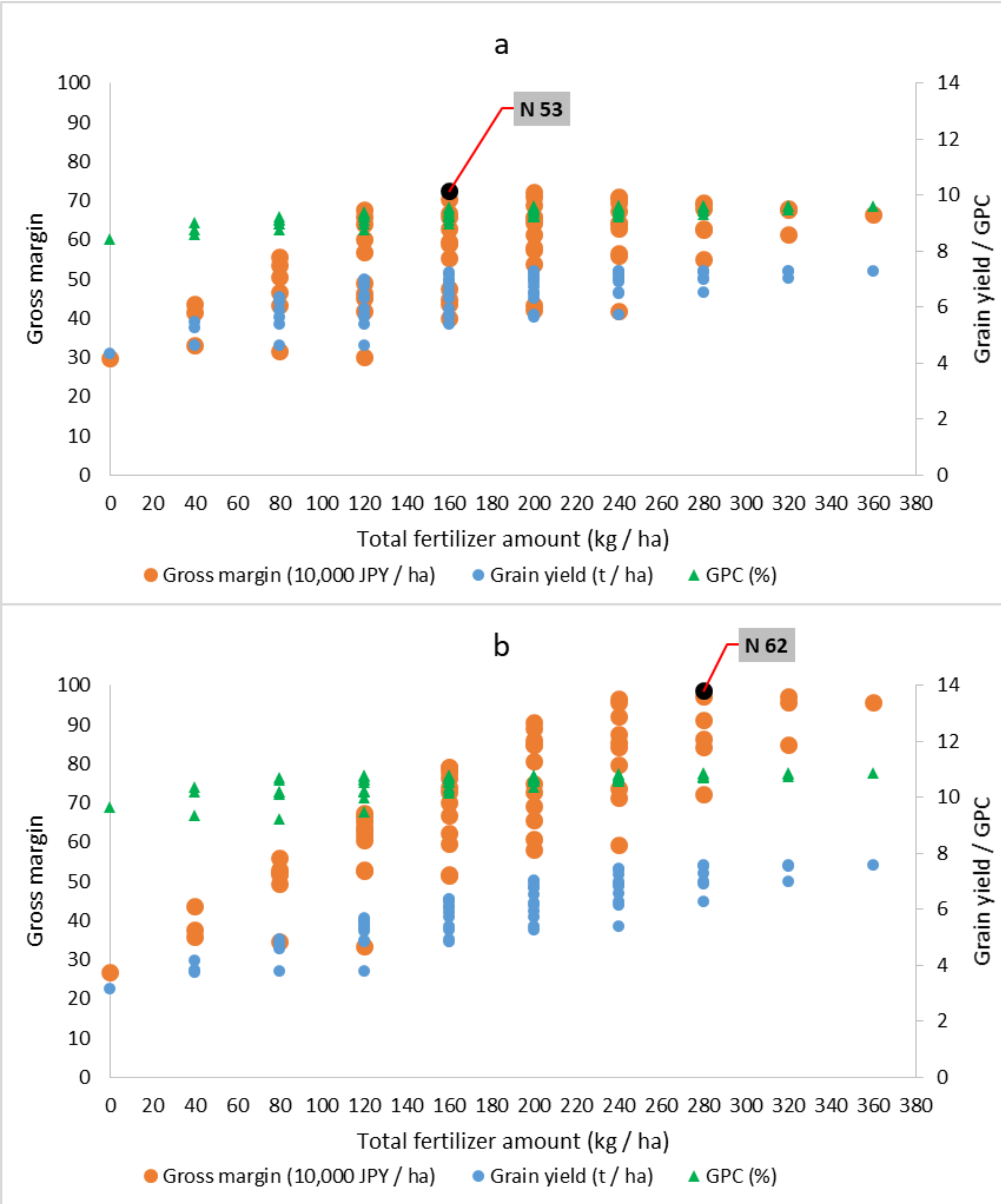


Figure 7.5 Variation of grain yield, GPC and gross margin with the amount of N applied. Primary Y-axis is gross margin (10,000* JPY ha^{-1}) secondary Y-axis is grain yield (t ha^{-1}), and GPC (%) and X-axis is the amount of N applied (0 – 360 kg ha^{-1}). Plot "a" denotes Kitahonami and plot "b" denotes Yumechikara. (grain yield, GPC and, gross margin values are average of 30 years under each N treatment (N1-N64))

Based on the fertilizer guidelines in Hokkaido, total 180 kg N ha^{-1} (Basal:40; Stem elongation:100; Flag leaf: 40) and 190 kg N ha^{-1} (Basal: 40; Stem elongation: 90; Flag leaf: 60) were selected as the current farmers' practice (current fertilizer recommendations) for Kitahonami and Yumechikara respectively (Department of Agriculture, Hokkaido prefectural government, 2015), and then, additional simulations were conducted to compare the yield and other parameters under the optimal N application scheme elucidated in this scenario analysis and the current fertilizer practice.

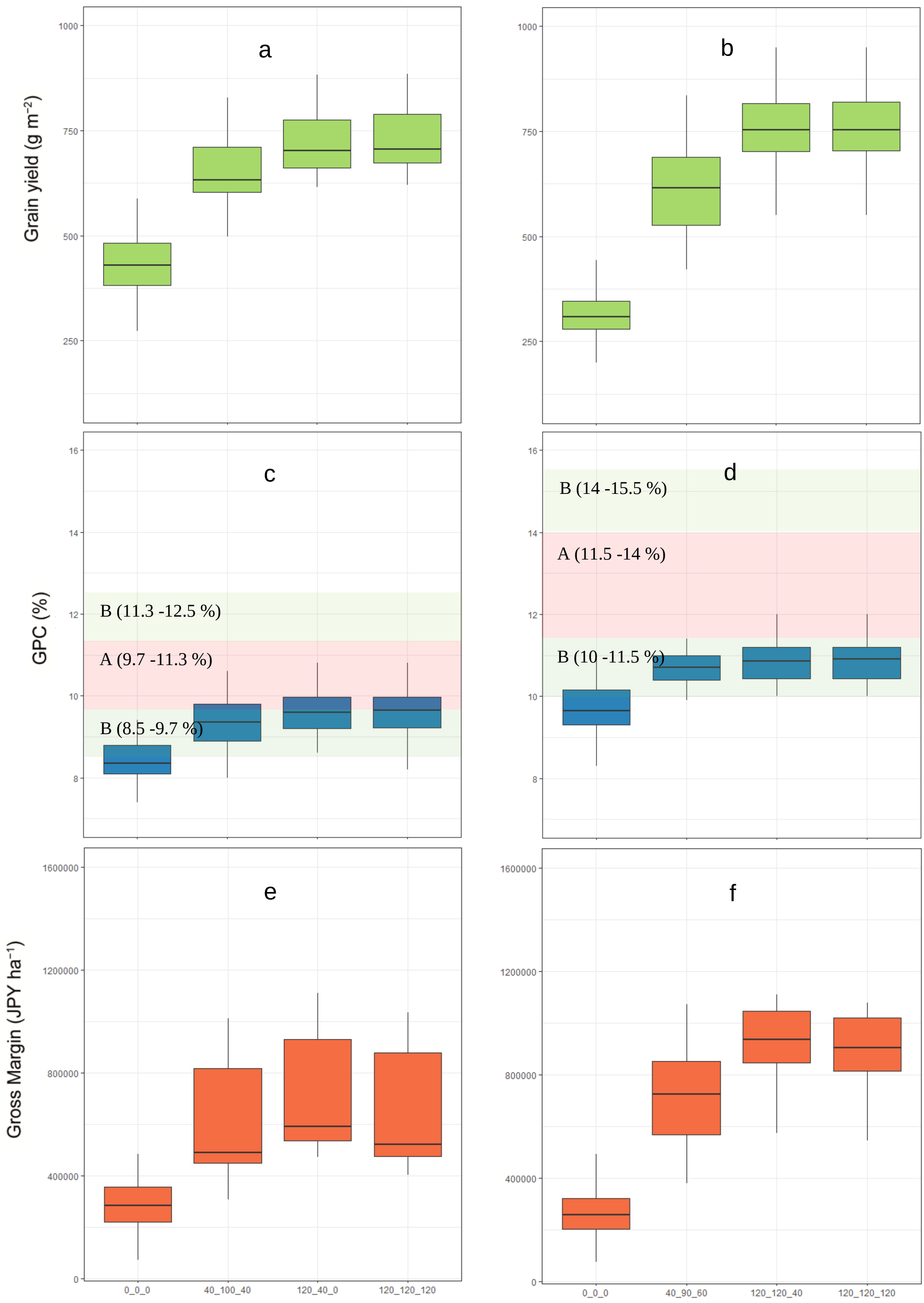
Variation of grain yield, GPC and, gross margin at the lowest (0_0_0), farmers' practice, optimum and, maximum (120_120_120) N levels for Kitahonami and Yumechikara are shown in Figure 7.6.

According to the simulation results, the median yield at farmers' N application scheme was 632.5 and 615.5 g m^{-2} for both Kitahonami and Yumechikara, respectively (Figures 7.6a and 7.6b). Whereas, the median grain yield at optimum N treatment was 701.7 and 754 g m^{-2} for Kitahonami and Yumechikara, respectively, or 10.9 and 22.5 % increase in comparison to the farmers' N application scheme. Median grain yield at maximum N treatment was similar to that of optimal N scheme for both varieties.

Median GPC was 9.3 % in Kitahonami and 10.7 % in Yumechikara at the farmers' practice (Figures 7.6c and 7.6d). 9.3 % GPC of Kitahonami and 10.7% of Yumechikara was exceeded the ranges of rank A quality bonus window of soft and hard wheat but within the ranges of B quality bonus window. At the optimal N application also, GPC of Kitahonami (9.6%) and Yumechikara (10.8%) was within rank B quality bonus window. Median GPC at maximum N scheme was equal to that of the optimal N level in both varieties.

Median gross margin was 490,521.8 and 725,457.1 JPY ha^{-1} for Kitahonami and Yumechikara respectively, at the farmers' N application scheme (Figures 7.6e and 7.6f). However, median gross margins at optimum N scheme was 591,344.1 and 936,539.8 JPY ha^{-1}

for Kitahonami and Yumechikara respectively, which is 20.5 % higher in Kitahonami and 29 % higher in Yumechikara compared to that at the farmers' N application scheme. Since neither yield nor GPC advantage increased at maximum N scheme compared to that at the optimum scheme, the gross margin rather tended to decrease owing to the increased cost of fertilizer.



a
b
c
d
e
f
Grain yield (g m^{-2})
GPC (%)
Gross Margin (JPY ha^{-1})
1000
750
500
250
16
14
12
10
8
1600000
1200000
800000
400000
0
B (11.3 -12.5 %)
A (9.7 -11.3 %)
B (8.5 -9.7 %)
B (14 -15.5 %)
A (11.5 -14 %)
B (10 -11.5 %)
0_0_0
40_100_40
120_40_0
120_120_120
40_90_60
120_120_40

Figure 7.6 Variation of grain yield, GPC and, gross margin at the lowest (0_0_0), farmers' practice (40_100_40 / 40_90_60), optimum (120_40_0 / 120_120_40) and, maximum (120_120_120) N levels for Kitahonami and Yumechikara. Plot "a, c and e" denotes Kitahonami and plot "b, d and f" denotes Yumechikara. Shaded areas in graph c and d denote the quality bonus windows. Pink denotes the rank A quality bonus and green denotes rank B quality bonus. The boxes present the 25-to-75 percentile, whiskers (i.e., the horizontal dashes linked to boxes by vertical lines) present the 10-to-90 percentile, the black line in the boxes is median.

In Chapter 6 it was demonstrated that the optimal N treatment varied for both hard and soft wheat grown in Kanto region due to year to year variation of climate. In order to evaluate the same effect for hard and soft wheat grown in Hokkaido, the optimum N treatment was determined for each year by comparing the gross margin of different treatments. Figure 7.7 shows the change of optimal N treatment over the 30 years together with the changes grain yield, GPC and gross margin of Kitahonami (a) and Yumechikara (b). Change in average annual temperature (AAT) and precipitation (AAP) is also plotted in the graphs for comparison. During the 30 years period both AAT and AAP showed an increasing trend for both Kitami (7.7a) and Sapporo (77b) areas of Hokkaido. The variability of the AAP among the years were very high. The increasing trend was significant only for AAT (Kitami: $y = 0.0366x - 66.6$, $P<0.01$; Sapporo: $y = 0.031x - 52.681$, $P<0.01$).

The most profitable N scheme (optimal) of each year for Kitahonami was mostly stable and total N rate of most profitable N treatment was 160 kg N ha^{-1} in 22 years (Figure 7.7a). Among those 22 years, 20 years had the same N scheme as optimum N scheme elucidated above, i.e., N 53 (120/40/0, total 160 kg N ha^{-1}). Out of 30 years, GPC of 13 years were within the rank A quality bonus window. The gross margin generally followed the same pattern of the grain yield.

The optimal N scheme of each year for Yumechikara also tended to stay at around N62 (120/120/40, total N rate was 280 kg N ha^{-1}) which was the optimum N scheme elucidated for Yumechikara. N62 was for 19 years among 30 years of total simulation period. It showed that out of 30 years, GPC of only 6 years were within the rank A quality bonus window. Similar to that of Kitahonami, the gross margin generally followed the same pattern of grain yield.

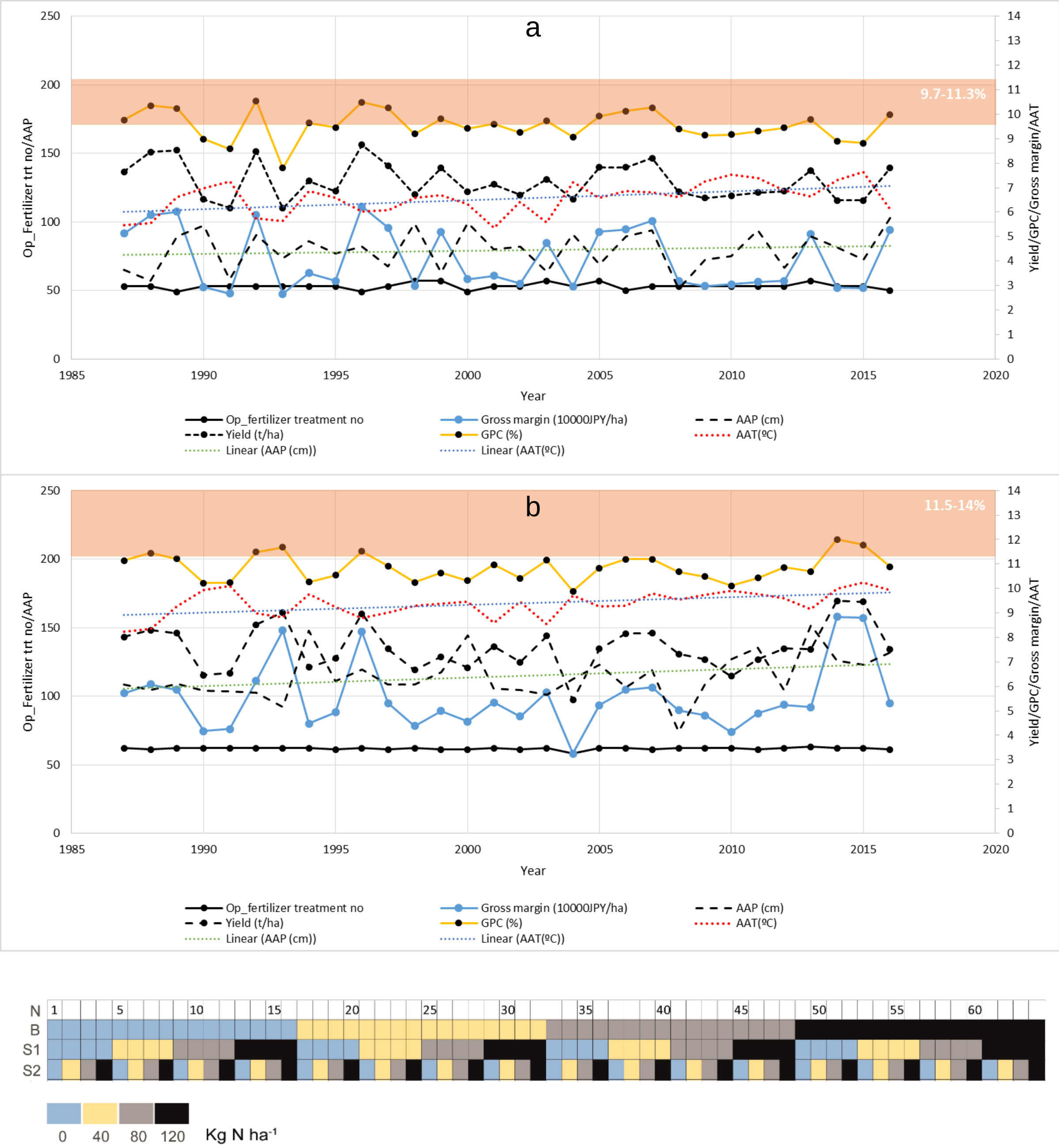


Figure 7.7 Change in optimal N application rate over the 30 years and respective grain yields, GPCs and gross margins of Kitahonami (a) and Yumechikara (b). Change in annual average temperature (AAT) and precipitation (AAP) is also indicated. Shaded area in orange is the rank A quality bonus window for both varieties. The patch chart below the figure with four colours shows the amount of N applied as basal (B), at stem elongation stage (S1), and at flowering (S2) under each N treatment.

7.4 Discussion

7.4.1 APSIM model calibration and validation of wheat growth in Hokkaido

In Chapter 4, calibration and validation of APSIM wheat model for the representative hard and soft wheat varieties grown in Kanto region was demonstrated. Results presented in this chapter is the first attempt to calibrate and validate APSIM wheat model for representative winter wheat varieties in Hokkaido region. Two major varieties in Hokkaido, Kitahonami (soft wheat) and Yumechikara (hard wheat) were used for this chapter. At present, 75% of the total wheat cultivation area is cultivated with Kitahonami and 9.5% of the total area is cultivated with Yumechikara, thus, these two varieties represent ca. 85% of the wheat growing area in Hokkaido (Nihei, 2012; Hokkaido Prefectural Government, 2017). In this chapter, Kitahonami and Yumechikara were calibrated and validated for the soil and climatic conditions in Kitami (Toumon-Kitami region) and Sapporo (Ishikari plain), respectively. These two sites are the centers of the two main wheat growing regions in Hokkaido. The calibration and validation was conducted with the experimental data from published literature of the respective varieties (Table 7.1). The different data sets were used for the calibration and validation. The validation was done for phenology, grain yield and, GPC at optimum sowing period. The cultivar specific parameters derived for Kitahonami and Yumechikara can be used for the future modelling research using APSIM model for the Hokkaido region.

Validation results showed that, RMSE for grain yield was 75 and 86 g m^{-2} for Kitahonami and Yumechikara, respectively. These RMSE values are comparable to the range of RMSE for grain yield reported in the literature (40 to 85 g m^{-2}) (Asseng et al., 1998; Asseng et al., 2000; Chen et al., 2010; Balwinder-Sing et al., 2011). As for GPC, RMSE for Kitahonami and Yumechikara were 1 and 0.5 %, respectively which was even lower than the range of the reported values (1.5 – 3.2 %) (Asseng et al., 1998; Asseng et al., 2000; Asseng et al., 2002). RMSE for phenology were 6 and 4 days for Kitahonami and Yumechikara respectively. Pre-harvest sprouting is one of the major problems in wheat cultivation for Hokkaido region (Yanagisawa et al., 2005). Therefore, accurate prediction of phenology is also vital as a decision support using crop growth models in Hokkaido.

Recently Honda et al. (2014) validated DSSAT model for Hokushin soft wheat variety for Obihiro region in Hokkaido. They reported 59-75 g m^{-2} of model mean absolute error (MAE) for grain yield and relatively larger MAE, between 19-27 days for phenology. Thus, in comparison to these results, APSIM model had a lower model error of predicting phenology over DSSAT model.

Model efficiency (ME) values between 0 and 1 are generally viewed as acceptable levels of performance, and model performance is regarded as satisfactory if ME > 0.50, good if ME > 0.65, and very good if ME > 0.75 (Moriasi et al., 2007). In the present result, ME for grain yield was 0.5 for Yumechikara, which is within the range of that reported by Chen et al. (2010) and Ahmed et al. 2016 (0.4-0.95), while that for Kitahonami was low (0.08). ME related to phenology and GPC were respectively, 0.88 and 0.98 for Kitahonami and, 0.94 and 0.3 for Yumechikara. Considering the fitness of observed and simulated values (Figure 7.1 and 7.2) and RMSE, the present validation is in a range of acceptable level.

7.4.2 Economic optima for the nitrogen application in Hokkaido

It was demonstrated in this chapter that the modelling approach applied for Kanto region in the previous chapters seems to be able to be applied to Hokkaido region. Hokkaido was selected because it is the largest wheat growing region in Japan having different climatic conditions from Kanto region such as low temperature in winter and snow cover.

Similar to Kanto region, economically optimum nitrogen application scheme was elucidated by scenario analysis, testing wide range of N application with different combinations of basal and split applications. The results would also provide guidance to increase profitability for the wheat farmers in the region by increasing yield and obtaining the benefits of quality bonus. Thirty years of daily historical weather data was used to test the effect of long-term climate variability on the effectiveness of each scenario.

The economically optimum N application rate derived from simulation was 280 and 160 kg N ha^{-1} in total for Yumechikara and Kitahonami wheat varieties respectively. The split N rates were 120-120-40 for hard wheat, and 120-40-0 for soft wheat (kg N ha^{-1} for basal, split at stem elongation stage and at flowering stage). With this optimum N application scheme, farmers can obtain maximum gross margin of 984,515.8 JPY for hard wheat and 722,926 JPY ha^{-1} for soft wheat.

The recommended fertilizer level in Hokkaido for Yumechikara is 190 kg N ha^{-1} (Basal: 40; Stem elongation: 90; Flag leaf: 60), (Department of Agriculture, Hokkaido prefectural government, 2015). Therefore, in comparison to the derived optimal N application rate, the current fertilizer recommendation is lower than that of the optimal rate (280 kg N ha^{-1}). However still the gap is lower than that was found in Kanto region for Yumeshiho (i.e., Optimal N rate is 280 kg N ha^{-1} and the current fertilizer recommendation is 100 kg N ha^{-1}).

In the case of Kitahonami, the current fertilizer recommendation is 180 kg N ha^{-1} (Basal: 40; Stem elongation: 100; Flag leaf: 40), (Department of Agriculture, Hokkaido prefectural government, 2015). The elucidated optimal N application for Kitahonami is 160 kg N ha^{-1}. Therefore, it can be said that with the current fertilizer recommendation level, the optimum N requirement can be met and current fertilizer recommendation is slightly higher than that of elucidated optimum N application rate.

According to the simulations results, Kitahonami is reaching to the saturation of the grain yield at around 160 kg N ha^{-1} fertilizer rate, therefore, there is no any economic gain could be achieved increasing the fertilizer rate beyond 160 kg N ha^{-1} fertilizer rate (Figure 7.5a). This is different from Yumechikara and other two varieties from Kanto region (Yumeshiho and Ayahikari). For them, yield saturation happed at higher N application rate (280 kg N ha^{-1}) (Figure 7.5b and 6.3). The possible reason for this difference with Kitahonami may be due to its higher nitrogen use efficiency. According to the literature, Kitahonami is characterised by higher grain yield and lower GPC (Yanagisawa et al., 2007 as cited in Fueki et al., 2015b). The higher grain yield is attributed to the larger sink capacity (higher number of grains per year and thousand grain weight) (Kasajima et al. 2016). Also, according to the Kasajima et al. (2016), the erect green leaves of Kitahonami can absorb radiation more effectively, leading to a higher net assimilation rate in the later grain filling phase and higher dry-matter production after the milk-ripe stage. The difference in performances of the two varieties in the model is expressed by cultivar parameters, i.e., “vernalization sensitivity”, “photoperiod sensitivity”, and “thermal time from beginning of grain filling to maturity” were lower for Kitahonami than Yumechikara whereas “maximum specific leaf area for delta LAI” and “potential grain filling rate” are higher for Kitahonami than Yumechikara (Table 7.3). Owing to these differences in cultivar parameters Kitahonami showed shorter growth duration, higher leaf area, shorter grain filling period and higher rate of grain filling compared to Yumechikara.

Average wheat yield in Hokkaido region is reported to be 440 g m^{-2} (MAFF, 2014). However, in the limited number of recent field experiments, wheat yield related to current fertilizer recommendation rates were reported to be 579 to 634 g m^{-2} for Kitahonami (Tsukamoto et al., 2017; Kasajima et al., 2016) and 617 g m^{-2} (Tsuji et al 2010) for Yumechikara. At the optimal N treatment derived from the scenario analysis, simulated yield showed to be increased (i.e., 701 and 754 g m^{-2}, respectively for Kitahonami and Yumechikara) than the average wheat yield in Hokkaido and the reported yields under above mentioned experimental conditions.

The simulated yield levels under optimal N treatment can be verified with existing reports in which nearly similar N applications were used; Fueki et al. (2015a) reported 731 g m^{-2}, grain yield with 160 kg N ha^{-1} N application for Kitahonami. Yoshihira et al. (2012) had reported, 650 g m^{-2}, grain yield with 220 kg N ha^{-1} N application for Yumechikara. Therefore, these field experimental results imply the reliability of the optimum N scheme derived from the scenario analysis.

The optimal N rate derived from the simulation analysis of this research suggested the advantage of increasing the total N application up to 160 kg N ha^{-1} and 280 for Kitahonami and Yumechikara, respectively, of which 120 kg N ha^{-1} to be applied as basal. This is in contrast to the fertilizer recommendations for Hokkaido (40 kg N ha^{-1} basal application). Watanabe (2012) suggested that any N amount applied higher than 40 kg N ha^{-1} would be remained in the soil unutilized by the plants and will be leached by the snow melt before plant started growing rapidly. Hence, these results have shown the need of further improvement in APSIM soil water and soil N modules to capture the soil water and N dynamics under snow cover and after snow melting (which is not considered by the current APSIM wheat model).

The highest gross margin which was resulted with optimum N scheme of Yumechikara (hard wheat) were higher than that of Kitahonami (soft wheat) owing to the higher quality bonus offered for hard wheat (Figures 7.5 and 7.6). With respect to the GPC contribution for gross margin, under the optimum N treatment, both Yumchikara and Kitahonami from

Hokkaido region resulted GPC belonged to the rank B quality bonus range for hard wheat (10 – 11.5 %) and soft wheat (8.5-9.7 %) which gave a 5.8% and 8.4 % less quality bonus compared to the premium quality bonus (rank A) respectively, for hard and soft wheat.

The simulation results showed that yearly optimal N application scheme tend to be relatively stable during 30 years period in Hokkaido varieties and it was at or closer to the optimal N scheme derived based on the average gross margin of 30 years, which is in contrast to the optimal N scheme for the varieties of Kanto which was more changeable for year to year owing to the inter-annual climate fluctuation (Figure 7.7).

7.5 Conclusions

The results of this chapter showed the implications of applying/extending the modelling approach for fertilizer recommendation of wheat in the Hokkaido region. The results of this simulation study at the representative sites indicated that economically optimum rate of total N application for Yumechikara (hard wheat) was 280 kg N ha^{-1}. The respective split N rates were 120-120-40 kg N ha^{-1} at sowing, at stem elongation stage and at flowering, respectively. With this optimum N treatment, the producers can obtain by 29 % higher median gross margin (one out of 2 year chance) than the gross margin which can be obtained with current fertilizer recommendations. The elucidated economically optimum N rate for Kitahonami (soft wheat) was lower than that of Yumechikara which was 160 kg N ha^{-1} (120-40-0 kg N ha^{-1} at sowing, at stem elongation stage and at flowering, respectively). The median gross margin increased was by 20.5 % for Kitahonami with that optimum N treatment. Thus, the use of APSIM model for decision support on N management helped to elucidate an optimum N application regime for typical hard and soft wheat varieties grown in Hokkaido region. For the future research it was suggested to include model improvements in APSIM to capture the soil N and water dynamics under snow cover and during the period of snow melt.

Chapter 8

General Discussion and Conclusions

This study focused on optimizing productivity and quality of wheat through modelling approach. Thus, this study consisted of three main parts: field experiments, model application and scenario analysis. The purpose of the field experiments using both hard and soft wheat varieties grown in Kanto area was to elucidate the effect of N management and late sowing conditions on yield, yield components, grain protein concertation, and seed emergence at low temperature. The model application part is comprised of parameterization and validation of APSIM model to the target wheat growth conditions, and in addition, improving the model to be better applied for late sowing conditions in Kanto region. The scenario analysis is comprised of N management decision support for both hard and soft wheat grown in Kanto region and, finally it was also tested the possibility of applying this modelling approach to the largest wheat producing prefecture, Hokkaido.

The objective of this chapter to discuss the implications that can be drawn from this study that would help to improve the wheat productivity in Japan and to provide insights on wheat research perspectives.

8.1 N management optima elucidated from modeling to improve the wheat productivity

Scenario analysis was conducted to find out the economically optimum N application scheme by testing the wider range of N treatments with different combinations of basal and split applications.

Table 8.1 summarizes the current N management scheme, elucidated optimal N management scheme for Kanto and Hokkaido regions and, percentage change of median gross margin that can be expected with optimal N scheme elucidated in this study.

The results of this simulation study indicated that economically optimum rate of total N application for both Yumeshiho (hard wheat) and Ayahikari (soft wheat) from Kanto region was 280 kg N ha^{-1} (Chapter 6, Figure 6.3). Split N rates were, however, different: 120-80-80 kg N ha^{-1} at sowing, at stem elongation stage and at flowering, respectively for Yumeshiho, and 120-120-40 for Ayahikari. With these optimum N treatments, the producers can obtain by 84.8 and 145.6 % higher median gross margin (one out of 2 year chance) for Yumeshiho and Ayahikari, respectively than that can be obtained by current fertilizer recommendations. (Figure 6.4 of Chapter 6, Table 8.1). The simulation results showed that yearly optimal N application scheme tend to change to some extent due to year to year climate variation during the 55 years period in both varieties. However during the average years it was at or closer to the optimal N scheme derived based on the average gross margin of 55 years (280 kg N ha^{-1}) (Chapter 6, Figure 6.5).

The economically optimum rates of total N application for Yumechikara (hard wheat) from Hokkaido region was 280 kg N ha^{-1} split to 120-120-40 kg N ha^{-1} at sowing, at stem elongation stage and at flowering, respectively. And that for Kitahonami was 160 kg N ha^{-1} 20-40-0 kg N ha^{-1} (Chapter 7, Figure 7.5). With these optimum N treatments, the producers can obtain by 29 and 20.5 % higher median gross margin (one out of 2 year chance) compared to the current level for Yumechikara and Kitahonami, respectively (Figure 7.6 of Chapter 7, Table

8.1). The simulation results showed that yearly optimal N application scheme tend to be relatively stable during the 30 years period in both varieties and it was at or closer to the optimal N scheme derived based on the average gross margin of 30 years (160 and 280 kg N ha^{-1}) (Chapter 7, Figure 7.7).

Table 8.1 Percentage change in median gross margin due to optimal N treatment for hard and soft wheat grown in Kanto and Hokkaido regions.

Region	Variety	Current N management scheme in the region (kg N ha^{-1})	Economically optimum N management scheme (kg N ha^{-1})	% increase of median gross margin due to optimal N scheme
Kanto	Ayahikari (soft wheat)	100 (80/20/0)[1]	280 (120/120/40)[1]	145.6
	Yumeshiho (hard wheat)	100 (80/20/0)[1]	280 (120/80/80)[1]	84.8
Hokkaido	Kitahonami (soft wheat)	180 (40/100/40)[2]	160 (120/40)[1]	20.5
	Yumechikara (hard wheat)	190 (40/90/60)[2]	280 (120/120/40)[1]	29.0

[1] Basal/Stem elongation/flowering
[2] Basal/Stem elongation/flag leaf

Thus, the use of APSIM model for decision support on N management helped to elucidate an optimum N application regime for typical hard and soft wheat varieties grown in Kanto and Hokkaido region even taking the long-term climate variation into account.

8.2 Implications of modelling approach on uplifting current yield levels

The Figure 8.1 shows the relationship between the amount of fertilizer applied and the average yield reported in Japan, European countries and New Zealand and the simulated median grain yield resulted from optimal N scheme derived with the scenario analysis.

It showed that amount of fertilizer applied in European countries and New Zealand are higher than that of Japan (FAO, 2016; FAO, 2002; Han and Dijk, n.d.; HGCA, 2009; Grinsven et al., 2012; Jones, 2013). Conventional lower fertilizer rates in Japan especially in Kanto region is usually attributed to the risk avoidance associated with lodging. Also, the national average wheat yield in Japan (4.1 t ha^{-1}) is lower than that in other major wheat producing countries indicated in the Figure 8.1 as was discussed in Chapter 6 (yield values are the three years mean value from 2014 to 2016; FAO, 2016).

As shown in Figure 8.1, the optimal N schemes elucidated from the modelling approach resulted in the increase of median yields of hard and soft wheat grown in Kanto and Hokkaido regions to the close levels of the yields of high yielding countries. The appropriate N management would be a promising approach to improve the wheat productivity in Japan, and modelling approach combined with field experimental knowledge would be a good method for providing decision support.

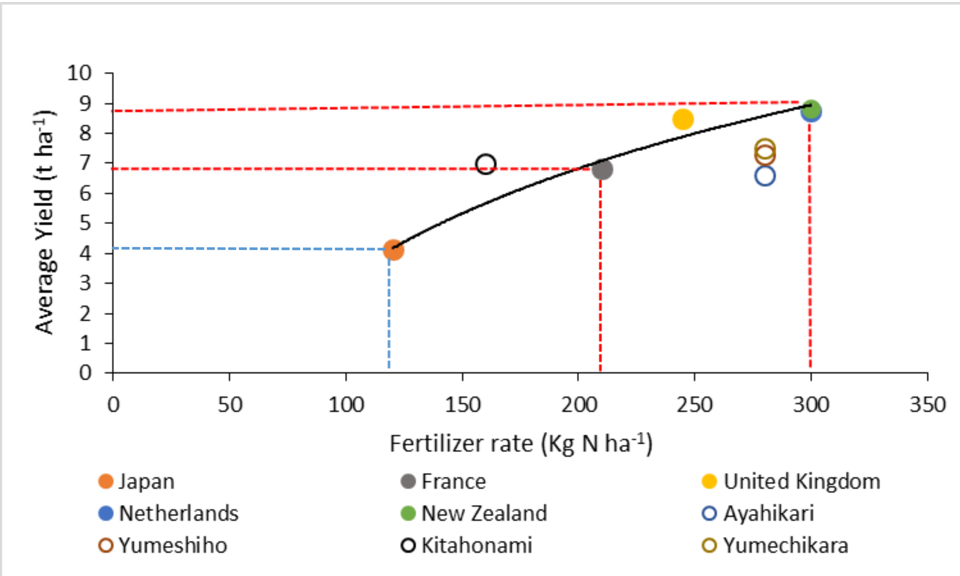


Figure 8.1 National average wheat grain yields (data points with close circles) Vs. Fertilizer application rates in Japan, France, Netherlands, New Zealand and United Kingdom and median grain yields of hard and soft wheat cultivars (data points with open circles) from Kanto and Hokkaido regions, resulted from simulated optimal N schemes .

8.3 Conclusions

This study focused on optimizing productivity and quality of wheat through modelling approach. Thus, the N management was considered as the main agronomical technology to evaluate the effects on increasing the grain yield and controlling GPC for the expected quality levels. Late sowing was also considered for the Kanto region since it is a concerned issue for producers in the region. Based on that, field experiments were conducted in the Kanto region to generate the field experiment knowledge. For the Hokkaido region, the data from the published research was obtained. Then APSIM crop model was calibrated and validated for both regions to get the confidence about the model accuracy and suitability of reproducing the field experiment knowledge in the simulations. With the acceptable validation results, the model was used to conduct scenario analysis to elucidate the economically optimum N schemes for the hard and soft wheat grown in Kanto and Hokkaido regions by taking the historical climate variation into account. Thus, by the modelling approach, this research demonstrated that, by optimum N management current average yield level of Japan could be increased to the closer level of that in the high yielding countries in the world with reasonable level of GPC, and there by increase the profitability of the producers.

This is the first study conducted, using a modelling approach to derive a decision support to improve the wheat productivity and quality in Japan considering both grain yield and GPC, to the best of my knowledge.

In this study, a model improvement was conducted with the inclusion of the algorism of reducing the plant density when the emergence was delayed at the late sowing conditions. The new algorithm was coded incorporating a quadratic function obtained from the field experimental results. To best of my knowledge, this is the first report of improving APSIM model by integrating an empirical model to correct the plant density at emergence due to the low temperature at emergence.

Concerning future research, it is suggested to extend and test this modelling approach mainly for the Kyushu and other wheat growing regions in Japan (with the validation for N movement in Japanese soil as well) and, to test the scenario analysis with generated forecasted weather data for forthcoming cropping season, for predicting optimal N management scheme, optimal sowing time, and phenology (flowering and maturity time) for coming season as a real-time decision support for the producers.

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