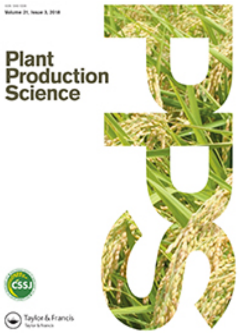

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The spatial patterns in long-term temporal trends of three major crops' yields in Japan

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ABSTRACT
Long-term trend of crop yields has been widely studied in global scales to find which crops and which geographic regions offer the best hope of meeting food demands, and which regions needed the most improvements. In this study, a mathematical method was applied to analyze spatial patterns in long-term temporal trends of three major crops' yields in Japan archipelago. The changes in annual yields of rice, wheat, and soybean over a period of about 60 years in all 47 prefectures of Japan was analyzed by using the data of agricultural records. For all the three crops, the nationwide yields previously improved, but currently were stagnating in Japan. The result suggests that the annual yields were not improving in 53, 85, and 89% of those prefectures in Japan for rice, wheat, and soybean, respectively. The spatial patterns in temporal trends show that the percentage of number of yield-not-improving prefecture was higher in low latitude regions than high latitude regions. These results highlight the increasingly difficult challenge of meeting the growing demands and stagnating supplies in daily staple foods not only for agricultural scientists but also for Japanese society.

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1. Introduction

Crop production in agriculture is directly related to food supply. As a result, the crop yield must be increased to meet the growing demands (Alexandratos, 1999; Cassman, 1999; Glover et al., 2012; Tilman et al., 2002) driven by the increasing human population, meat consumption, and biofuel use (Foley et al., 2011; Godfray et al., 2010; Holdren & Ehrlich, 1974; Pingali, 2006; Tilman et al., 2011). The global population is expected to grow to 9 billion by 2050 (Hafner, 2003; United Nations Population Division, 2000), and global agricultural production may need to be increased by 60–110% to meet these increasing demands from 2005 to 2050 (FAO, 2009; OECD/FAO, 2012; Tilman et al., 2011).

However, the total global crop production increased by only 28% between 1985 and 2005 (Foley et al., 2011). Recently, several studies reported that the yield of many crops, such as rice, maize, and cereal (barley, oat, rye, and wheat), may be not increasing any more in some regions around the world (Brisson et al., 2010; Cassman, 1999; Finger, 2010; Lin & Huybers, 2012; Peltonen-Sainio et al., 2009; Ray et al., 2012, 2013). In addition, some reports have suggested that those crop yields may be stagnating or declining in many important global croplands (Brisson et al., 2010; Cassman, 1999; Finger, 2010; Hafner, 2003; Kendall & Pimentel, 1994; Peltonen-Sainio et al., 2009), in particular for three key crops – maize, rice, and wheat (Tilman et al., 2011). The yields were reported that either never improved, stagnated, or collapsed across 24–39% of maize-, rice-, wheat-, and soybean-growing areas including the most important cropland areas over the world during the period 1961–2008 (Ray et al., 2012).

Japan is a country having one of the highest levels of crop yields per unit area over the world because only 12% of its land is suitable for cultivation (USDA, 2012). The overall agricultural self-sufficiency rate in Japan is ~50% on fewer than 14 million acres lands cultivated (USDA, 2012). Rice is considered the most important crop for Japan's society. In 2014, Japan dedicated 10.7 million ha to rice cultivation (FAO, 2015), which ranks the 17th in the world. The other two important food staples in Japanese food culture, wheat and soybean, their ranks of production are the 35th and 47th in the world in 2014 (FAO, 2015).

Recently, long-term trends of crop yields has been widely studied by scientists using the records in global scales (Aizen et al., 2008; Godfray et al., 2010; Lesk et al.,

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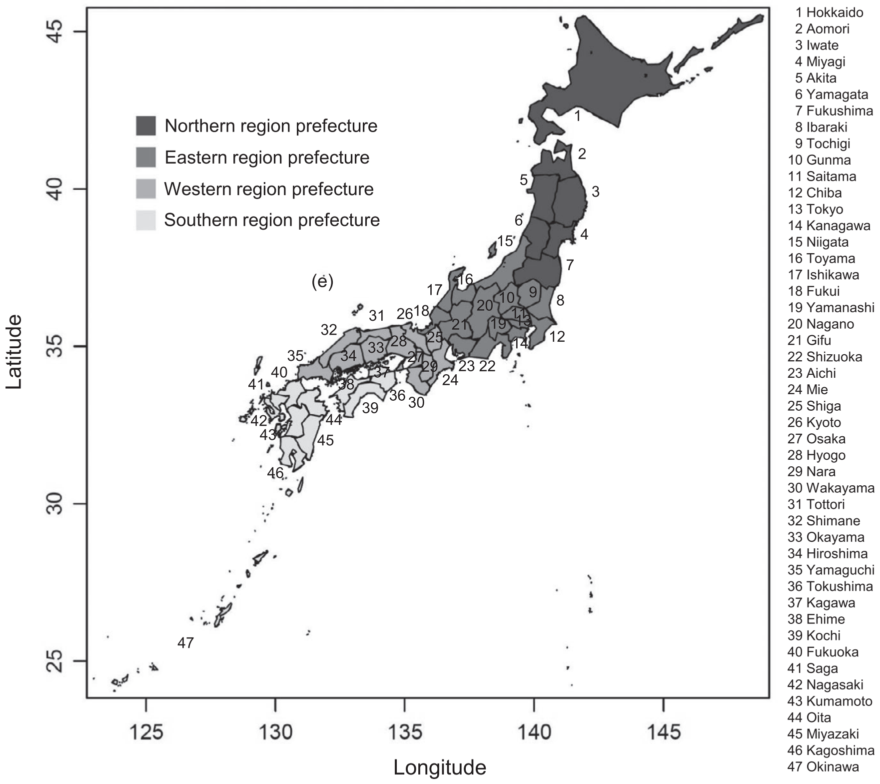

Figure 1. Map of 47 prefectures in Japan and their regions classified in the study.

2016; Ray et al., 2012, 2013; Tilman et al., 2011). By analyzing spatial patterns in long-term temporal trends of crop yield, the aims of this work are to find which crops and which geographic regions in Japan archipelago offer the best hope of meeting food demands and which regions are improvements most needed. First, I analyze changes in annual yields of rice, wheat, and soybean over a period of ~60 years in all the 47 prefectures of Japan by using the data obtained from the governmental official website. The crop yield trends for each prefecture are classified into four categories including (1) increasing, (2) stagnating, (3) collapsed, and (4) never improved, by using parsimonious regression models of increasing order. Last, I map these different temporal trends in prefectures and discuss their spatial patterns for all the three crops. The results of this research highlight the increasingly difficult challenge of meeting the growing demands and stagnating supplies in daily staple foods for Japanese society.

2. Material and methods

2.1. Data of crop yield

Crop yield data of rice, wheat, and soybean in all the 47 prefectures in Japan (Figure 1) were downloaded from the official website of Ministry of Agriculture, Forestry and Fisheries, Japan (available online from http://www.maff.go.jp/). Fifty-nine years' data of rice from 1958 to 2016 were available for each prefecture except for Okinawa (43 years' data). Sixty-nine years' data of soybean from 1948 to 2016 were available for each prefecture except for Okinawa (28 years' data). Fifty-nine years' data of wheat from 1958 to 2016 were available for 38 prefectures (Hokkaido, Aomori, Iwate, Miyagi, Akita, Yamagata, Fukushima, Ibaraki, Tochigi, Gunma, Saitama, Chiba, Tokyo, Kanagawa, Yamanashi, Nagano, Gifu, Shizuoka, Aichi, Mie, Shiga, Kyoto, Hyogo, Nara, Tottori, Shimane, Okayama, Hiroshima, Yamaguchi, Kagawa, Ehime, Fukuoka, Saga, Nagasaki, Kumamoto, Oita, Miyazaki, and Kagoshima). In addition, 55, 49, 52, 58, 48, 52, 58, 58, and 43 years' data of wheat were available for Niigata, Toyama, Ishikawa, Fukui, Osaka, Wakayama, Tokushima, Kochi, and Okinawa, respectively.

2.2. Yield trend analysis

This study was inspired by Ray et al. (2012), who used parsimonious regression models to examine the trends in crop yields for maize, rice, wheat, and soybeans across the globe extending over the period 1961–2008. Yield trends were analyzed using these parsimonious regression models of increasing order for: an intercept-only model (Equation (1)), a linear model (Equation (2)), a quadratic model (Equation (3)), and a cubic model (Equation (4)).

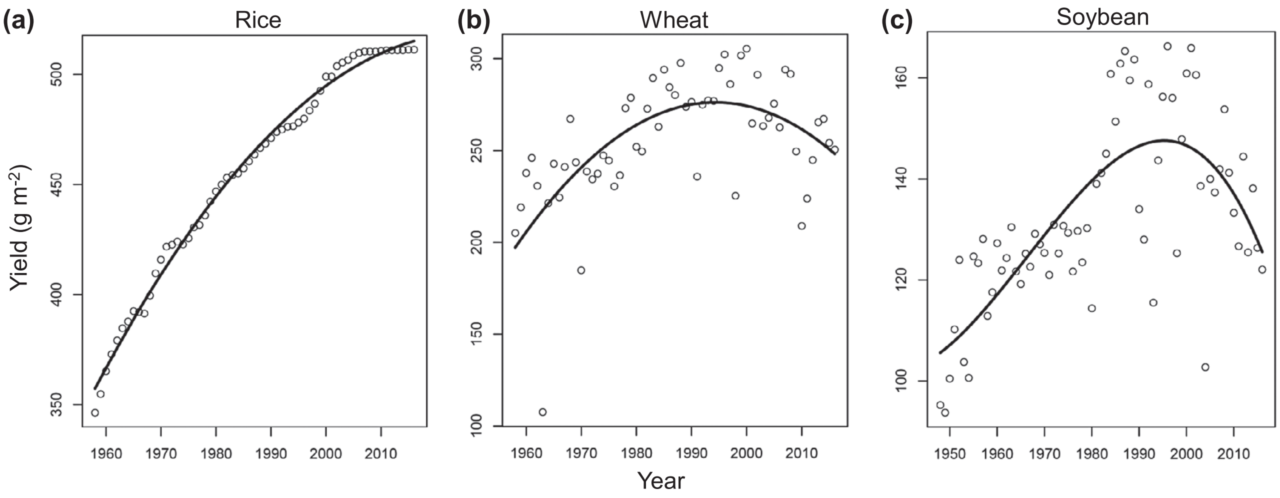

Figure 2. Temporal variations in prefectures average of yearly crop yield in Japan from 1958 to 2016 for (a) rice and (b) wheat and from 1948 to 2016 for (c) soybean. The curve in each panel is the statistical model fits to the data.

$$Y = a \tag{1}$$

$$Y = a + bt \tag{2}$$

$$Y = a + bt + ct^2 \tag{3}$$

$$Y = a + bt + ct^2 + dt^3 \tag{4}$$

Here, Y is the yield (g m^{-2}), t is the year, a is the intercept, and b, c, and d are the coefficients of regression.

2.3. Choosing the statistical model that best represents production trends

The Akaike Information Criterion (AIC) developed by Akaike (1974) was used to decide which statistical model fitted the observed data best, and computed AIC (Equation (5)) for each of the above four models (Equations (1)–(4)):

$$\mathrm{AIC} = n\log\left(\frac{ss}{n}\right) + 2p \tag{5}$$

Here, ss is residual sum of squares, n is the sample size, and p is the number of parameters. The model with the minimum AIC was chosen as the best representation of the production trend for a given prefecture. All calculations and data analyses were performed using R v 3.0.2 (R Development Core Team, 2013).

2.4. Classification of production trends

Based on the chosen model parameters, crop yield trends were classified into four main categories: increasing, stagnating, collapsed, and never improved. These classifications are defined as follows. (1) Yield increasing: (i) when the chosen model was linear, with a positive slope; (ii) when the chosen model was quadratic with a positive quadratic term, and the yield for the 2010s had reached the high values in the 1950s; (iii) when the chosen model was cubic, with the peak of yield after 2010. (2) Yield stagnating: (i) when the chosen model was quadratic with a negative quadratic term, and the yield for the 2010s had not reached the low values in the 1950s, and (ii) when the chosen model was cubic, and the yield for the 2010s had not reached the low values in the 1950s with the peak beyond 2010. (3) Yield collapsed: (i) when the chosen model was linear, with a negative slope; (ii) when the chosen model was quadratic, with a negative quadratic term, and the yield for the 2010s had reached the values in the 1950s; (iii) when the chosen model was cubic, and the yield for the 2010s had reached the low values in the 1950s. (4) Yield never improved: when the chosen model was intercept-only model.

3. Results

3.1. Long-term trends of crop yield in Japan

According to Figure 2(a), the annual temporal variation in prefecture average of rice yield in Japan ranged between 346 (in 1958) and 511 (in 2015) g m^{-2}, with a mean of 455 and standard deviation 48, during the 59-year period between 1958 and 2016. The chosen model for the average rice yield was quadratic with a negative quadratic term, and the yield for the 2010s had not reached the low values in the 1950s. That is, the yield previously improved, but currently was stagnating. As for wheat, the annual temporal variation in prefecture average of yield in Japan ranged between 108 (in 1963) and 306 (in 2000) g m^{-2}, with a mean of 258 and standard deviation 33, during the 59-year period between 1958 and 2016 (Figure 2(b)). The chosen

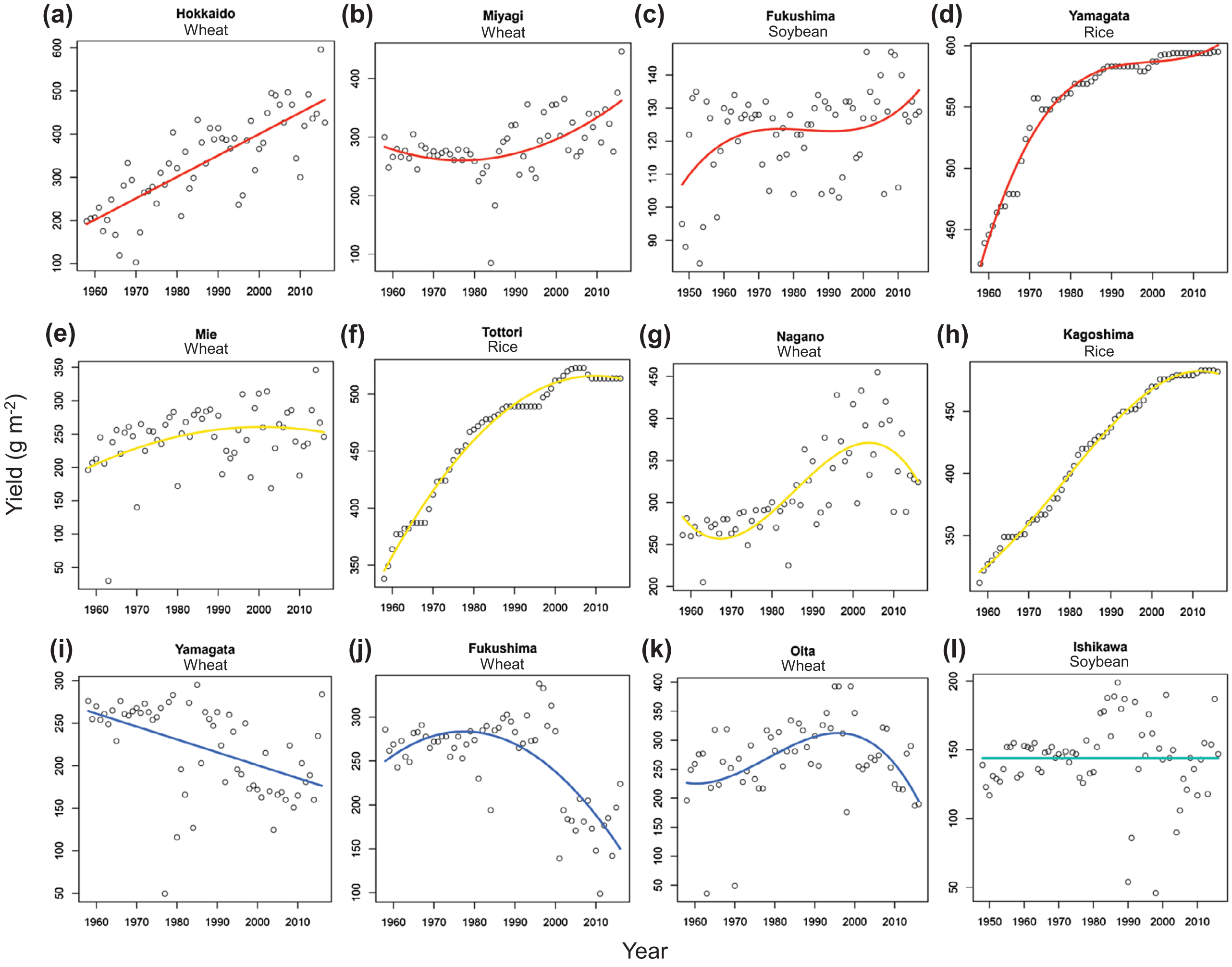

Figure 3. Illustration examples of the best-fit regression models for crop yield trends: (a)–(d) Yield increasing. (e)–(h) Yield stagnating. (i)–(k) Yield collapsed. (l) Yield never improved. (l) Intercept-only model. (a) and (i) Linear model. (b), (e), (f), and (j) Quadratic model. (c), (d), (g), (h), and (k) Cubic model. Color codes correspond to the temporal pattern illustrated in Figure 4. The points represent the observations.

model for the average wheat yield was quadratic with a negative quadratic term, and the yield for the 2010s had not reached the low values in the 1950s. The yield previously improved, but currently was stagnating. As for soybean, the annual temporal variation in prefecture average of yield in Japan ranged between 94 (in 1949) and 166 (in 1996) g m^{-2}, with a mean of 133 and standard deviation 18, during the 69-year period between 1948 and 2016 (Figure 2(c)). The chosen model for the average soybean yield was cubic, and the yield for the 2010s had not reached the low values in the 1950s with the peak beyond 2010. The yield previously improved, but currently was stagnating.

3.2. Long-term trends of crop yield in each prefecture

The yield trends in Japan's prefectures were divided into four types. Figure 3 illustrates examples for each type: (1) Prefectures (wheat in Hokkaido and Miyagi, soybean in Fukushima, and rice in Yamagata) where yield were still increasing (Figure 2(a)–(d)). (2) Prefectures (wheat in Mie and Nagano and rice in Tottori and Kagoshima) where yield previously improved, but currently was stagnating or declining (has not reached the level in the 1950s) (Figure 2(e)–(h)). (3) Prefectures (wheat in Yamagata, Fukushima, and Oita) where yield decreased since the 1950s (Figure 2(i)), or initially increased and then collapsed to the level in the 1950s (Figure 2(j) and (k)). (4) Prefectures (soybean in Ishikawa) where yield never improved (Figure 2(l)). All graphics of the 47 prefectures for three crops can be found in Figures S1–S3.

In total, there are three types of increasing trends: Figure 2(a) shows the linear trend with a positive slope; Figure 2(b) shows the quadratic trend with a positive quadratic term, and the yield for the 2010s had reached the high values in the 1950s; Figure 2(c) and (d) show the cubic

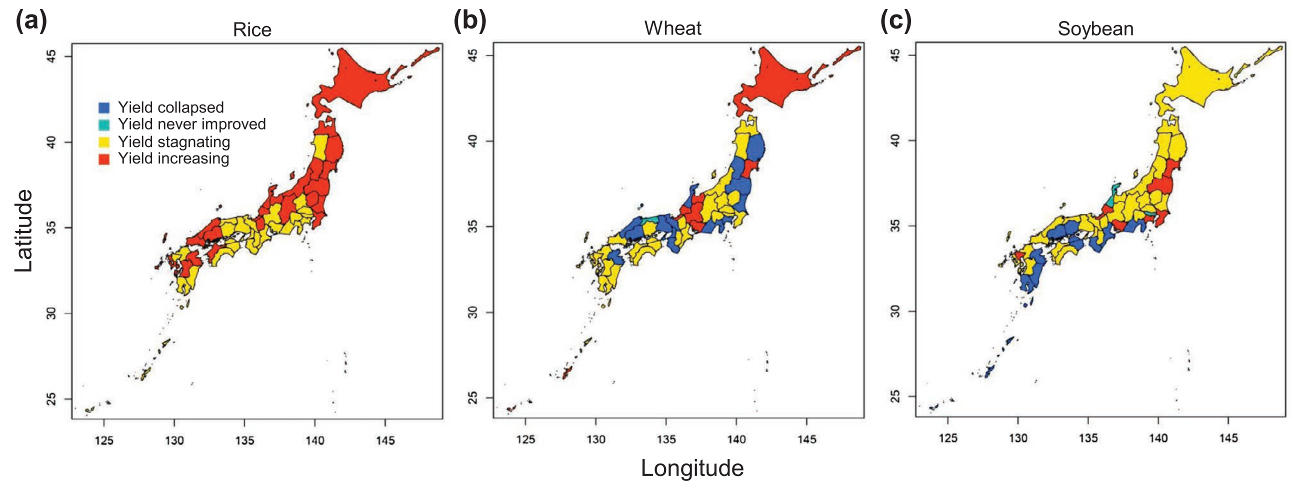

Figure 4. Spatial patterns in temporal trend of crop yield for 47 prefectures in Japan for (a) rice, (b) wheat, and (c) soybean.

Table 1. Crop yield status (percentage of number of prefecture in each region) in Japan.

	Rice				Wheat				Soybean			
Region	I	S	C	NI	I	S	C	NI	I	S	C	NI
Northern	85.7	14.3	0.0	0.0	28.6	28.6	42.9	0.0	28.6	71.4	0.0	0.0
Eastern	50.0	50.0	0.0	0.0	25.0	56.3	18.8	0.0	12.5	68.8	6.3	12.5
Western	33.3	66.7	0.0	0.0	0.0	41.7	50.0	8.3	0.0	66.7	33.3	0.0
Southern	33.3	66.7	0.0	0.0	8.3	83.3	8.3	0.0	8.3	41.7	50.0	0.0
Nationwide	46.8	53.2	0.0	0.0	14.9	55.3	27.7	2.1	10.6	61.7	23.4	4.3

Notes: I – yield increasing; S – yield stagnating; C – yield collapsed; NI – yield never improved.

trend with the peak of yield after 2010. There are two types of stagnating trends: Figure 2(e) and (f) show the quadratic trend with a negative quadratic term, and the yield for the 2010s not reaching the low values in the 1950s; Figure 2(g) and (h) show the cubic trend with the yield for the 2010s not reaching the low values of the 1950s. There are three types of collapse trends: Figure 2(i) shows the linear trend with a negative slope; Figure 2(j) shows the quadratic trend with a negative quadratic term, and the yield for the 2010s reaching the low values in the 1950s; Figure 2(k) shows the cubic trend, with the yield for the 2010s reaching the low values of the 1950s. A list of classification of production trends and the coefficient of determination (R^2) for all prefectures of all crops can be found in Table S1.

3.3. *Spatial patterns in long-term trends of crop yield*

Within the 59-year period of analysis, rice yield was increasing and stagnating in 47 and 53% of the prefectures in Japan, respectively, and it has not collapsed in any prefecture (Figure 4(a) and Table 1). Wheat yield was increasing, stagnating, and collapsed in 15, 55, and 28% of the prefectures, respectively, and it has never improved in one prefecture (Figure 4(b) and Table 1). Within the 69-year period of analysis, soybean yield was increasing, stagnating, and collapsed in 11, 62, and 23% of the prefectures, respectively, and it has never improved in two prefectures (Figure 4(c) and Table 1). Yields were stagnating in more than half of all prefectures in the country for all the three crops. Rice yield was increasing in near half of the prefectures. On the other hand, the number of yield-decreasing prefecture were more than that of the yield-increasing prefecture for wheat and soybean.

The result shows some patterns of spatial differences in temporal trend for the regions located in different latitude (Figure 1). For rice and wheat yields, the percentage of number of yield-increasing prefecture was higher in high latitude regions (northern and eastern regions), but the percentage of number of yield-stagnating prefecture was higher in low latitude regions (southern and western regions, Table 1). For soybean, both of the percentages of number of yield-increasing and -stagnating prefectures were higher in high latitude regions, but the percentage of number of yield-decreasing prefecture was higher in low latitude regions (Table 1).

4. Discussion

Growing conditions of crops have changed over time due to the changes in the natural environment and cultivation (Craufurd & Wheeler, 2009; Lobell & Burke, 2010; Lobell et

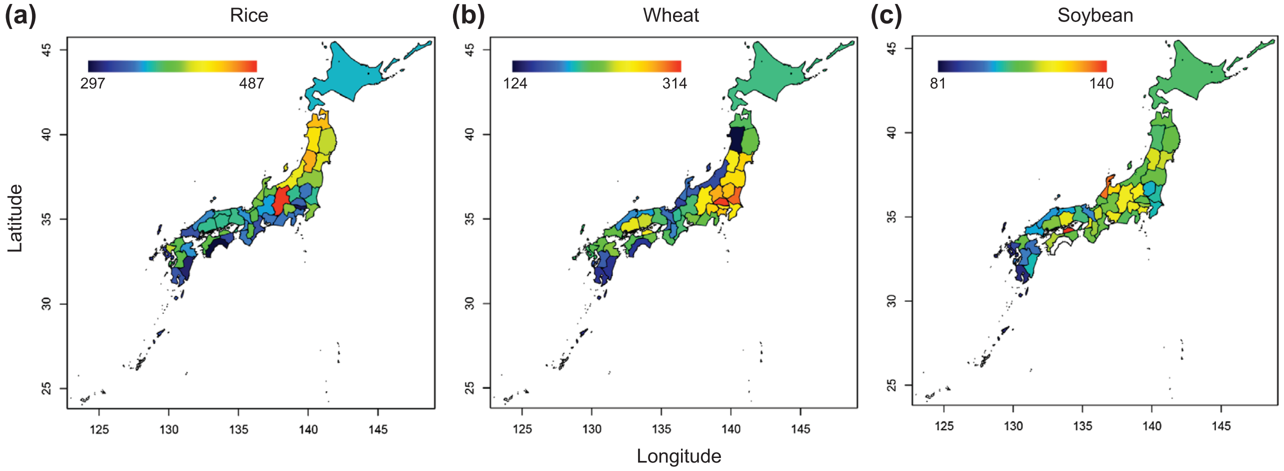

Figure 5. Spatial patterns in original crop yield (10-year averaged yield in early years) for 46 prefectures in Japan for (a) rice (1958–1967), (b) wheat (1958–1967), and (c) soybean (1948–1957).

al., 2011; Shimono et al., 2010; Walther et al., 2002). The yield of crop is affected by climatic factors such as annual rainfall (Drury & Tan, 1994; Spiecker, 1995), solar radiation (Lobell et al., 2013; Welch et al., 2010), and air temperature (Lobell & Field, 2007; Matsui et al., 2001). Besides, the long history of cultivation and the geographical variation of climatic conditions, such as the number of rainy days during cropping season (for example, the length and starting day of Asian Rainy Season vary from area to area in different years), also result in large spatial differences in crop yield (Lobell et al., 2009). Furthermore, the impact of global warming can negatively affect crop yields on a global scale (Chen, 2016; Rosenzweig & Parry, 1994). To discuss these issues, a large number of studies have analyzed the contributions of climatic factors for rice (Morita et al., 2016; Peng et al., 2004; Shimono, 2008; Shimono et al., 2010), wheat (Asseng et al., 2015), and soybean (Egli, 2008a, 2008b). In addition to the climatic factors, the extent of crop yield variation may vary geographically according to the types of cultivation, nitrogen fertilization, and soil type and fertility (Adams et al., 1998; Aydinalp & Cresser, 2008; Chen et al., 2014; Fuhrer, 2003). Contribution of cultivar differences has also been reported as an important factor on crop yield for rice (Peng et al., 1999; Saitoh et al., 1993; Zhang & Kokubun, 2004), wheat (Zhou et al., 2007; Ziska, 2008), and soybean (Matsuo et al., 2016, 2017; Ziska & Bunce, 2000). In order to analyze so many factors accompanied with huge datasets, models of crop growth are required to estimate and to predict how crop yield responds to the natural environment and cultivation.

The result suggested that the annual yields were not improving in 53, 85, and 89% of the prefectures in Japan for rice, wheat, and soybean (Table 1). To see whether the prefecture which originally had high yield is in increasing trend or not, 10-year averaged yield for each prefecture in the early period (1958–1967 for rice and wheat; 1948–1957 for soybean) were calculated as the original yield for each crop (Figure 5). For rice, the prefectures which originally had high yield (high during 1958–1967) are Nagano, Niigata, and the prefectures in northern region except Hokkaido. For wheat, the prefectures which originally had high yield (high during 1958–1967) are mostly the prefectures in eastern region, and Miyagi, Yamagata, and Fukushima in northern region. For soybean, the prefectures which originally had high yield (high during 1948–1957) are Kagawa, and some prefectures in eastern region. The yields of rice in those prefectures which originally had high yield were still increasing (Figures 4 and 5). However, for wheat and soybean, yields in those prefectures which originally had high yield were either stagnating or collapsed.

Hokkaido is one of the leading producers of crop in Japan (Chen, 2016). The yields of rice and wheat were still increasing in Hokkaido currently (Figure 4). Miyagi and Fukui are the only two yield-increasing prefectures for all the three crops (Figure 4). In Japan, eating quality has been suggested as one of the most important factors for the production. Koshihikari is a famous rice strain mainly grown in Niigata; it is the most popular and expensive strain in Japan (Ebitani et al., 2005). The fame and the high quality of this strain are due to the ideal growing conditions in Niigata (Ishizaki et al., 2005). Nagano prefecture has the largest yield of rice in Japan due to its rivers and complicated water channels designed to bring nutrient-rich water to the crops. Nagano has a high elevation basin surrounded by mountains; thus, the area experiences large differences in temperature between day and night that provide ideal growing conditions for crops (JMA, 2016). The yield of wheat collapsed in most of the prefectures in Kinki and Chūgoku regions (Shimane, Hiroshima, Kyoto, Osaka, Hyogo, and Wakayama, Figure 4). Because wheat is a long-day plant and can grow among a wide range of area, sunshine hours and daily radiation may be the deciding factors for the decline of yield (Bannayan et al., 2003). The yield of soybean collapsed in most of the prefectures in Kyushu (Oita, Miyazaki, and Kagoshima) and some in southern Japan (Figure 4). The collapse of yield may be related to the changing temperature in growing stage for soybean (Juang, 1993).

The results of this study showed that nationwide yields previously improved, but currently was stagnating for all the three crops in Japan. The annual yields were not improving in more than half of the prefectures in Japan for rice, wheat, and soybean. The result showed that the percentage of number of yield-not-improving prefecture was higher in low latitude regions than high latitude regions for the three crops in Japan. New investments and strategies to increase or maintain production in the high-performing areas are required, while simultaneously preserving a sustainable environment and cultivation for all crops.

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