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# Time series analysis of temperature and rainfall-based weather aggregation reveals significant correlations between climate turning points and potato (*Solanum tuberosum* L) yield trends in Japan

Seiji Shimoda[a,*], Hiromitsu Kanno[b], Tomoyoshi Hirota[c]

[a] *Hokkaido Agricultural Research Center, Memuro Research Station, NARO, (HARC/M/NARO), Shinsei-Minami, Memuro, Kasai, Hokkaido 082-0081, Japan*
[b] *Institute for Agro-Environmental Sciences, NARO, (NIAES/NARO), Kannondai, Tsukuba, Ibaraki 305-8666, Japan*
[c] *Hokkaido Agricultural Research Center, NARO, (HARC/NARO), Hitsujigaoka, Toyohira, Sapporo, Hokkaido 062-8555, Japan*

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ABSTRACT

Potato (*Solanum tuberosum* L.) yield per unit area in Hokkaido, Japan used to be the highest in the world; however, it has levelled off recently. The objectives of this study were to determine how recent climate variations drive potato yields and to understand the causes for this tendency of yield to level off. We used the 1-km mesh resolution for meteorological data; aggregation was performed for each municipality based on annual potato cultivation area; yield data were obtained from crop statics of Tokachi and Okhotsk regions in Hokkaido for the years 1986–2014. Potato yield was not only determined by temperatures during plant growth, as expected, but also by temperatures before planting. Probable yield inflexion point corresponded with increase in late summer temperature from the year 2000 onward. The negative correlation between spring and summer temperatures during the years 2000–2014 resulted from patterns of warm spring/cool summer or cool spring/hot summer, linked to the Inter-decadal Pacific Oscillation. A cool spring delayed planting and germination, whereas a hot summer shortened the growth period, causing the lowest yield in the year 2010. High temperatures in summer have encouraged farmers in Japan to implement adaptation strategies, such as earlier planting. As early plantation does not necessarily reduce time to sprout nor does it promote a longer growth period, the recent climate trend exacerbated potato yield responsiveness to summer temperature. As a result, increasing temperatures in summers from the late 2000s and unaltered spring temperatures as well as a shift in cultivars have caused potato yields in eastern Hokkaido to drop below those of other countries where potato yields are high. Detection of decadal climate shift as a planned-scale strategy and enhancement of drainage as a farm-scale strategy could effectively improve regional potato yield despite climate change.

## 1. Introduction

Global warming has become a serious issue for agriculture systems not only in tropical and subtropical regions, but also in temperate regions (Teixeira et al., 2013). Results from crop modelling exercises in the IPCC AR4 showed that small beneficial effects on rainfed crop yields may be expected in mid- and high-latitude regions with moderate-to-medium regional increases in temperature (1–3 °C), along with associated increases in $CO_2$ concentration and changes in precipitation (Rosenzweig et al., 2014). An understanding of recent climate trends would allow a more accurate assessment of the recent changes in the yield of many crops (Lobell and Field, 2007). The long-term effects of climate change on crop yield have often been quantified using time-series analysis (e.g. Olsen et al., 2011; Brown, 2013. Zhao et al., 2016). A significant break point in weather conditions may alter the sensitivity of crop yield to climatic conditions during the several-decadal-period. Decadal periods of rapid warming, or even cooling, are not inconsistent with a long-term warming trend (England et al., 2014). Recent analyses of climate model-simulations suggest that hiatus decades are linked to negative phases of the Inter-decadal Pacific Oscillation (IPO). There is an accelerating trend in the effects of equatorial Pacific winds on sea level trends and changes in ocean circulation after 21th century (England et al., 2014). Depending on the effects of the equatorial Pacific or global circulation fields, or both, the climate in Japan varies inter-annually (Urabe and Maeda, 2014). Kanno (2013) showed strongly negative inter-annual correlations between spring and summer air

*Abbreviations:*IPO, Inter-decadal Pacific Oscillation

* Corresponding author.
*E-mail address:* sss@affrc.go.jp (S. Shimoda).

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temperatures, beginning in 1998, in northern Japan (including Hokkaido). There was a particularly highly significant negative correlation between April and August temperatures (r = -0.8) (Kanno, 2013). From the viewpoint of inter-annual variation, many studies have focused on how spring weather in cold snowy zones influences the survival of overwintering crops and orchard trees (e.g., Shimoda et al., 2015a; Nemoto et al., 2016). However, early spring weather may affect farmer spring management decision making, such as timing of tillage and planting. Conditions in early spring are currently underrepresented in such studies, because potatoes were usually not planted at that time in Hokkaido; however, modeling of summer crop yields should consider these conditions. Analysis of the associations between monthly weather and crop yield allows examination of decadal time scales and determination of the climatic drivers of crop yield.

At present, potato (*Solanum tuberosum* L) ranks 4th in food crop production and is the most important non-grain crop worldwide (FAOSTAT, 2017). The peak potato-growing latitude in the northern hemisphere (52% of the total potato-growing area in the world) ranges between 44 °N and 58 °N, which is the summer crop production zone (Hijmans, 2003). As potatoes grow best in cool seasons, under conditions free from both heat and frost (Haverkort et al., 2013), world production is likely to be affected by increasing global temperature, which may cause 18% to 32% decrease in global potato yield (Hijmans, 2003). Throughout the summer growing season, high temperatures may lead to a shift in assimilate allocation from the tubers to the foliage (Krauss and Marschner, 1984). Up until the late 1980s, potato yield per unit area was higher in Hokkaido, northern Japan, than that in the United States and western European countries (Mori et al., 2007). However, yield in the United States and western Europe gradually increased afterwards, mainly due to the introduction of improved cultivars, use of fertilizers, and better irrigation systems (Bohl and Johnson, 2010; Pehrson et al., 2010), showing a similar trend as world potato yield (Appendix Fig. A1). The productivity of potato farms in Hokkaido has been levelling off more than over the last two decades, whereas in most countries potato productivity has been increasing over the same period (FAOSTAT, 2017).

In Hokkaido, potatoes are grown in the summer, under cool climate. Production in this region accounts for nearly 80% of the total Japanese annual potato production (MAFF, 2016). Improvement in crop management enhanced increased potato yield in Hokkaido until the early 1980s due to improved agricultural equipment and increasing fertilizer utilization (Doi, 1994). However, in general, the application of N, P, and K fertilizers gradually decreased from 1985 to 2000, as evaluations by the Ministry of Agriculture showed that soils in Hokkaido did not require such high fertilization rates, given their rich nutrient conditions (MAFF, 2000). Yield improvement usually reflects continuous innovation in agricultural technology combined with the introduction of new cultivars (Haverkort and Struik, 2015). Since the Hokkaido region is a rain-fed potato production area due to its humid climate, and because farmers still plant the same old cultivars, potato yield may be strongly sensitive to climatic conditions, irrespective of improvements in cropping system. Indeed, elevated atmospheric $CO_2$ and $O_3$ concentration affect, both positively and negatively, the photosynthetic responses in potato (Lawson et al., 2001; Vandermeiren et al., 2005). Increasing atmospheric $CO_2$ concentration around the world basically tends to enhance photosynthesis; moreover, an increasing trend in $O_3$ concentration in Hokkaido (Nagashima et al., 2017) might have had a slightly positive effect on potato yield. However, the length of the potato-growing season has become limited by unusually hot summers following unusually long winters in mid-latitude locations, such as Hokkaido (Haverkort et al., 2013).

We investigated the relationship between meteorological and potato yield anomalies based on a 29-year database to determine how recent climate variations drive potato yields and to understand the causes for potato yield levelling off in Hokkaido. We focused on the temperature threshold for potato growth as meteorological data. Stol et al. (1991) suggested that the daily threshold minimum and maximum temperatures for potato growth were above 5 °C ($T_{min} > 5$) and below 28 °C ($T_{max} < 28$), respectively. These threshold values are useful to identify periods with temperatures suitable for potato growth. Partitioning of dry matter to the foliage in potato plants remains constant at 0.8 below an average temperature of 15 °C ($T_{ave} < 15$), and decreases at higher temperatures (Bodlaender et al., 1964; Haverkort, 1990). Understanding of the effect of long- and short-term meteorological variability on crop performance will be critical for agronomic management decision making and for selecting the best-suited cultivars.

## 2. Materials and methods

### *2.1. Weather data*

Weather conditions for agricultural fields were extracted from 1-km-resolution time-series daily weather data for the years 1986–2014 in eastern Hokkaido, northern Japan. Meteorological data was obtained from Mesh-AMeDAS (Seino, 1993), which include the 1-km mesh resolution for daily mean air temperature (°C), sunshine duration (h), solar radiation (MJ $m^{-2}$), rainfall (mm), and rain days (number of days with more than 1 mm rain- or snowfall) as well as land use. We applied monthly mean data on weather parameters to analysis climatic drivers of potato yield. Municipal mean weather data for agricultural upland was obtained from Mesh-AMeDAS land use data. Weather aggregation was performed for each municipality according to the annual potato cultivation area in each case (Shimoda et al., 2015b), which integrated as 1-month or 3-month dataset in the units of the Tokachi and Okhotsk regions of eastern Hokkaido. Flowering and harvesting usually take place approximately from July to September in eastern Hokkaido, so those months may represent the environmental conditions during the development of the potato tubers in Hokkaido (Noda et al., 2012). Furthermore, the number of days with minimum air temperature below 5 °C ($T_{min} < 5$), average air temperature above 15 °C ($T_{ave} > 15$), and maximum air temperature above 28 °C ($T_{max} > 28$) were obtained from the daily meteorological mesh dataset. Similar to mean weather data, weather aggregation was performed for each municipality, which integrated as 3-month dataset in the regions.

### *2.2. Regional cultivar data*

Cultivation area and yield data were obtained from the Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF, 2016). Regional potato cultivation area in the year 2014 was 22,045 ha in the Tokachi region, and 17,393 ha in the Okhotsk region, both in eastern Hokkaido. A potato-breeding project began in 1902 in Hokkaido. Among the earliest cultivars developed were ‘Irish Cobbler’ and ‘May Queen,’ which are still the major cultivars grown for table use (Mori et al., 2015). Indeed, ‘Irish Cobbler’ and ‘May Queen’ were the leading potato cultivars in the Tokachi region of eastern Hokkaido throughout the study period. Cultivation area of each cultivar is expressed by the unit of Hokkaido (Hokkaido, 2017). The starch production cultivar ‘Benimaru’ was released in 1938. ‘Benimaru’ was a leading starch production cultivar until 1995 (Appendix Fig. A2a), when the cultivar ‘Konafubuki’ was released and gradually introduced; it now represents almost 60% of cultivation in the Okhotsk region of eastern Hokkaido (Hokkaido, 2016). Old table-use cultivar ‘Irish Cobbler’ peaked in 1997 and then its cultivation gradually decreased, while food processing cultivar ‘Toyoshiro’ still was planted in some 7500 ha (Appendix Fig. A2b).

In Hokkaido, the pre-emergence growth stage corresponds with April and May, the haulm stage largely corresponds with June and early July, and the tuber growth stage generally takes place after July. Growth duration from planting was approximately 120 to 140 days (Deguchi et al., 2016). The phases of haulm growth and tuber growth may be closely interrelated and overlapping. We obtained dates of planting and emergence for the unit of eastern Hokkaido from reports by MAFF during the period 1985–1991 (MAFF, 1992) and from the Hokkaido Agricultural Extension Center during the period 1995–2000, and 2006–2014 (Hokkaido, 2017). These dates have been reported for the unit of regions (Tokachi and Okhotsk, respectively) by MAFF and for the unit of eastern Hokkaido (combined Tokachi with Okhotsk regions). Published results were integrated and estimated by weighting with area each 3 and 5 local blocks in Tokachi and Okhotsk regions (MAFF, 1992). We were not able to find the report for 1992–1994, 2001–2005. More than half the soils in the region are of the humid types (50.7% for Fluvisols and 4.0% for Fibric Histosols) in the Tokachi region (Appendix Table A1), and there are various types in the Okhotsk region (Hokkaido Central Agricultural Experiment Station, 2008).

### 2.3. Statistical analysis

Statistical analyses were performed with R software version 3.3.2. (R Foundation for Statistical Computing, Vienna, Austria). Pearson's correlation test was used to assess statistical significance ($p$ value < 0.05) between correlation coefficients to analyze the relationship between each possible pair of monthly datasets of mean air temperatures (from April to September; after snowmelt to harvest of potatoes), and to analyze the relationship between planting/sprouting date and April, and April–May mean air temperatures. Time-series data of potato yield and weather data were found to have a significant trend, so they were also evaluated with the analysis of break point test present in the Strucchange library of R statistical software (R Core Team, 2014). The package has been used to detect the structural changes within the adjusted time series and then adjusting a linear model to each segment. Trend analyses of yield and weather data are described in terms of increased and decreased periods, depending on the sign of the regression coefficient estimated within each segment.

## 3. Results

### 3.1. Change in regional potato yield in Hokkaido

Change point analysis showed that there were some change points in potato yield during the 55-year period under study in eastern Hokkaido (Fig. 1). Agricultural civil engineering works improved field environmental conditions around the first change point, in 1967/68; then, increase in application of chemical fertilizers and fungicides, together with improvement of drainage, further enhanced potato yield in mid 1970s, and finally, the introduction of large agricultural machinery improved the level of efficiency control over field management in mid 1980s (Doi, 1994). After this third change point, potato yield in the region stopped increasing and began to level off. Regarding this levelling off phase since 1986, a new change point in potato yield was detected in 2008/09 in the Tokachi region, whereas two breakpoints were detected in 1995/96 and 2008/09, in the Okhotsk region (Fig. 2).

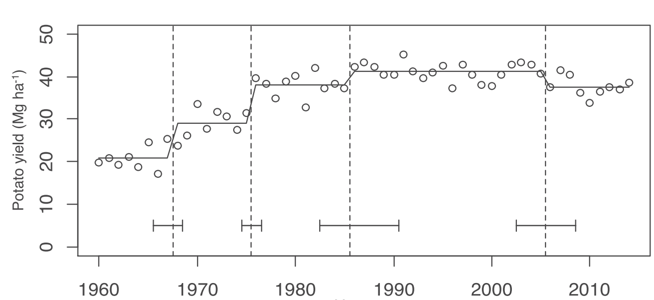


**Fig. 1.** Change point analysis of the time series for potato yield in eastern Hokkaido, Japan. The horizontal line shows breakpoints with a confidence of 95%.

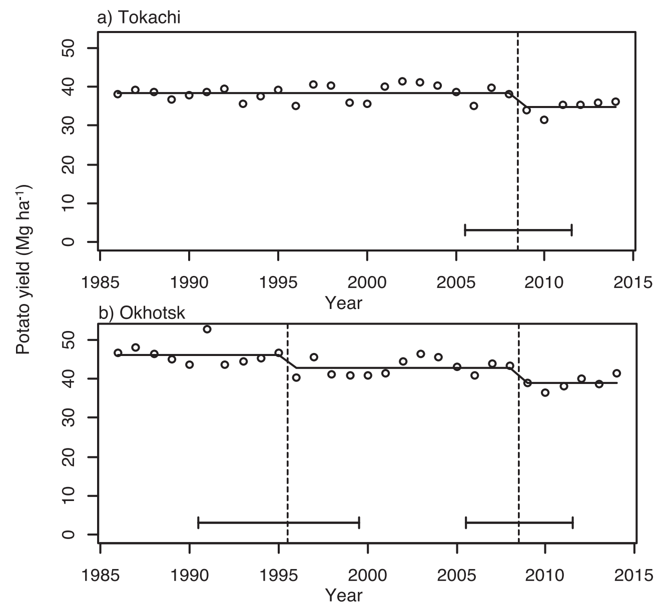


**Fig. 2.** Change point analysis of the time series for potato yield in a) Tokachi and b) Okhotsk regions. The horizontal line shows breakpoints with a confidence of 95%.

### 3.2. Time series of discontinuous change in air temperature

With regard to the levelling off phase beginning in 1986, a change point in average air temperature during Jul-Sep was detected in 2009/10, in both regions, whereas there was no change point during Apr–Jun in either region (Fig. 3a and b). Similarly, a change point in days of $T_{max} > 28$ was detected in 2009/10 during Jul-Sep in the Tokachi region (Fig. 4a). In Okhotsk region, a change point in days of $T_{max} > 28$ °C and $T_{ave} > 15$ °C was detected in 1997/98 during Apr-Jun (Fig. 4b and d). Further, a change point in days of $T_{ave} > 15$ °C during Jul-Sep was detected in 2005/06 and 2006/07 in Tokachi and Okhotsk regions (Fig. 4c and d). Time series of days of $T_{min} < 5$ °C did not show any breakpoint through the period under study (Fig. 4e and f).

### 3.3. Anomaly of monthly mean data for air temperature

In Hokkaido, including northern Japan, warm springs followed by cool summers or cool springs followed by hot summers are a regular occurrence. Subsequently, correlations were calculated between monthly mean data for temperatures in eastern Hokkaido, for each pair of months within the 29-year period under study. We observed a significant, positive correlation between pairs of monthly mean datasets for air temperature on August and September ($r = 0.53$, $p < 0.05$), and equally significant negative correlations between pairs of monthly mean datasets for air temperature on April and August ($r = -0.53$, $p < 0.05$), despite the fact that these months are in different seasons (Fig. 5a).

There is an accelerating trend in the effects of equatorial Pacific easterly winds (England et al., 2014), which explains why the climate in Japan has varied inter-annually since the late 1990s (Kanno, 2013; Urabe and Maeda, 2014). This indicates that the mean air temperature anomaly for 2000–2014 shows a highly significant negative correlation ($r = -0.89$, $p < 0.001$) between April and August in that year, in eastern Hokkaido (Fig. 5b). In summary, a cool spring often coincided with a hot summer during the period 2000–2014. Kanno (2013) reported that correlation coefficients of monthly mean data for surface air temperatures between April and August was −0.83 from 1999 to 2011 in northern Japan. Our results of strong association of temperature in April with August did not contradict those of Kanno (2013).

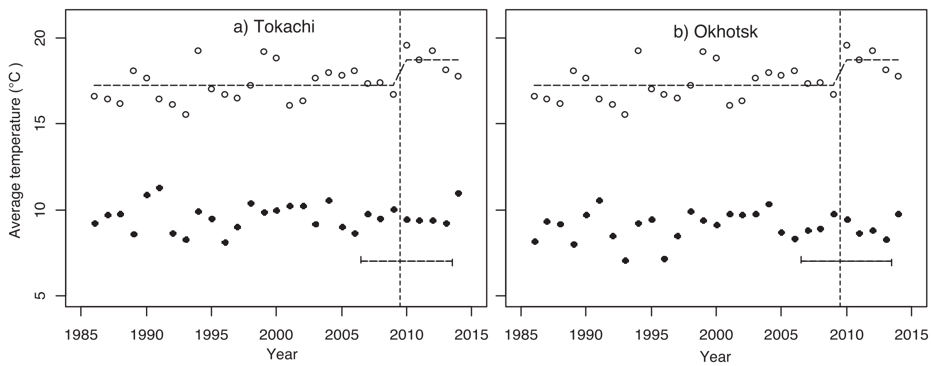


**Fig. 3.** Time series of the average temperature ($T_{ave}$) during Apr–Jun and Jul–Sep in a) Tokachi and b) Okhotsk regions. Black and white circles represent plots during Apr–Jun and Jul–Sep, respectively. The horizontal dotted lines represent the mean values for the periods before and after the change point, respectively. The horizontal dotted bars represent a confidence level of 95%.

### 3.4. Yield response to 1-month and 3-month mean data for air temperatures

The relationships between potato yield and 1-month and 3-month mean values for air temperature were investigated based on the consideration of inter annual temperature variations. Potato yield showed a significant positive correlation with monthly mean values for air temperature in April, in the Tokachi region ($r = 0.57$, $p < 0.01$) and in May, in the Okhosk region ($r = 0.38$, $p < 0.05$) (Fig. 6a). A Significant negative correlation was identified between yield and mean air temperature in August ($r = 0.45$ and 0.38, $p < 0.05$) in both, the Tokachi and Okhotsk regions, and in September ($r = 0.41$, $p < 0.05$), in the Tokachi region (Fig. 6a). Significant positive correlations were observed between yield and 3-month air temperature during Jul–Sep in Tokachi ($r = 0.50$, $p < 0.01$) and Okhotsk ($r = 0.46$, $p < 0.05$) regions (Fig. 6b). 3-month air temperature during April–June was not significantly associated with yield in either region (Fig. 6b).

During the entire 29-year period under investigation, overall mean potato yield was 37.6 Mg ha$^{-1}$ and 42.9 Mg ha$^{-1}$ in Tokachi and Okhotsk regions, respectively (Table 1). After 1986, the lowest yields in both regions were recorded in 2010, 31.5 Mg ha$^{-1}$ and 36.6 Mg ha$^{-1}$ in Tokachi and Okhotsk regions, respectively. These results indicate that the year when the highest yield was obtained in Okhotsk (1991)

a) 1986-2014

| | Apr | May | Jun | Jul | Aug |
|---|---|---|---|---|---|
| May | 0.27 | | | | |
| Jun | -0.09 | 0.15 | | | |
| Jul | -0.14 | 0.09 | 0.13 | | |
| Aug | -0.53 | 0.01 | 0.28 | 0.21 | |
| Sep | -0.09 | 0.01 | 0.07 | 0.31 | 0.53 |

b) 2000-2014

| | Apr | May | Jun | Jul | Aug |
|---|---|---|---|---|---|
| May | 0.07 | | | | |
| Jun | -0.38 | -0.18 | | | |
| Jul | -0.16 | -0.08 | 0.25 | | |
| Aug | -0.89 | -0.31 | 0.37 | 0.23 | |
| Sep | -0.32 | -0.38 | 0.00 | 0.35 | 0.47 |

**Fig. 5.** Correlation coefficients between each possible pair of monthly data for mean air temperatures in the period, a) 1984–2014, and b) 2000–2014. Black-framed and white number boxes indicate statistical significance ($p < 0.05$).

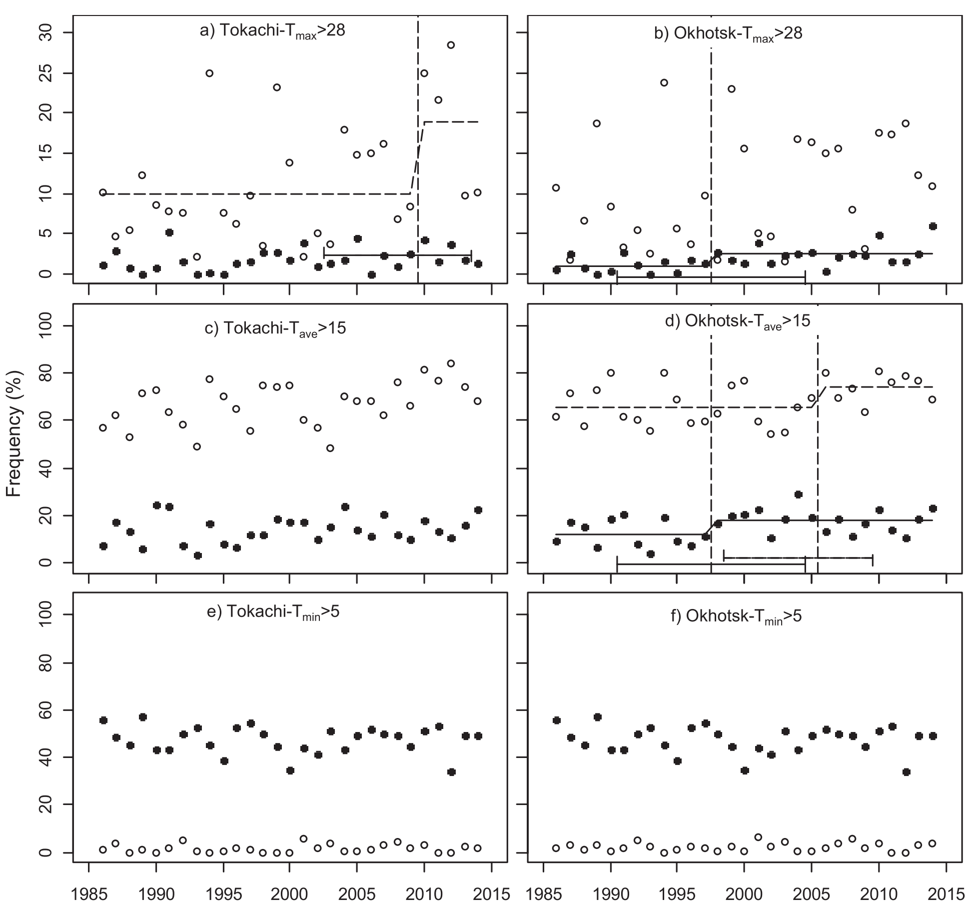


**Fig. 4.** Time series of the frequency of daily maximum temperature above 28 °C ($T_{max} > 28$) in a) Tokachi and b) Okhotsk regions; average temperature above 15 °C ($T_{ave} > 15$) in c) Tokachi and d) Okhotsk regions, and minimum temperature below 5 °C ($T_{min} < 5$) during Apr–Jun and Jul–Sep in e) Tokachi and f) Okhotsk regions. Black and white circles represent plots during the period Apr–Jun and Jul–Sep. The horizontal solid and dotted lines represent the mean values for the periods before and after the change point during Apr–Jun and Jul–Sep, respectively. The horizontal solid and dotted bars represent a confidence level of 95% during Apr–Jun and Jul–Sep, respectively.

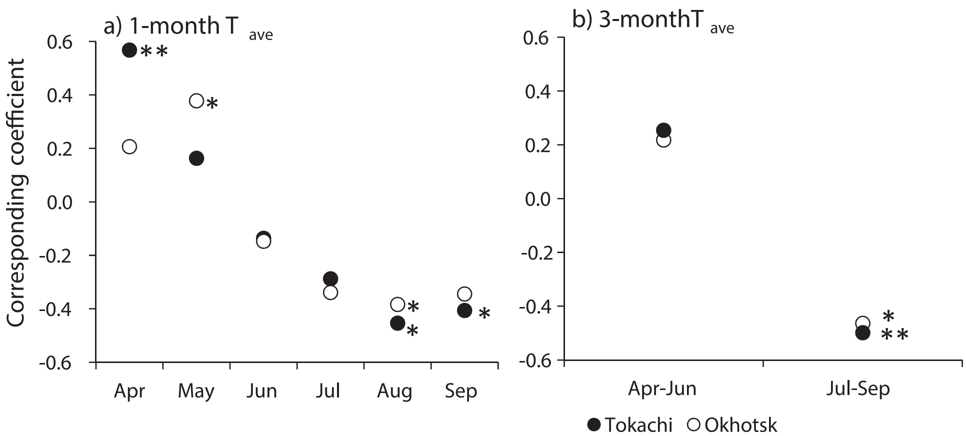


**Fig. 6.** Time series of correlations between potato yield and a) 1-month and b) 3-month (during Apr–June and July–September) mean air temperature during the period 1984–2014. * and ** indicate significant correlations ($p < 0.05$ and $p < 0.01$) between potato yield and weather conditions during Apr–June and July–September.

**Table 1**
Mean, highest, and lowest values of potato yield (annual) and air temperatures (for April–June and July–September).

| Yield and Air temp | Period | Region | Ave. | ± S.E | Highest | (year) | Lowest | (year) |
|---|---|---|---|---|---|---|---|---|
| Yield (Mg ha$^{-1}$) | | Tokachi | 37.6 | ± 0.5 | 41.5 | (2002) | 31.5 | (2010) |
| | | Okhotsk | 42.9 | ± 0.6 | 52.2 | (1991) | 36.6 | (2010) |
| Air temp (°C) | Apr to Jun | Tokachi | 9.6 | ± 0.2 | 11.3 | (1991) | 8.1 | (1996) |
| | | Okhotsk | 9.0 | ± 0.2 | 10.6 | (1991) | 7.1 | (1993) |
| | Jul to Sep | Tokachi | 17.5 | ± 0.2 | 19.6 | (2010) | 15.6 | (1993) |
| | | Okhotsk | 17.4 | ± 0.2 | 19.2 | (1994) | 15.7 | (1993) |

corresponded with the years of highest air temperature in April–June, over the 29-year period under scrutiny. Air temperature in July--September peaked in 1994 and 2010 in Okhotsk and Tokachi regions, respectively (19.2 °C and 19.6 °C), the same year lowest yields were obtained in both regions (Table 1).

### 3.5. Planting and sprouting time

Spring air temperature affected planting and sprouting time. Average date of planting and sprouting were 3rd of May and 2nd of June, respectively, over 20 years (1985–1991, 1995–2000, and 2006–2014). Planting and sprouting time significantly depended on air temperature in April and April–May in each period (1985–1991, 1995–2000, and 2006–2014) (Fig. 7). According to Kooman and Haverkort (1995), effective temperature determines the time between planting and emergence. From this point of view, the relationship between planting and emergence was suitable for May; however, air temperature in May did not significantly depend on sprouting time ($p > 0.05$ in the period of 1995–2000 and 2006–2014).

### 3.6. Time series of discontinuous changes in solar radiation and rainfall

Solar radiation showed a decreased in 1991/1992 during Apr-Jun in the Tokachi region (Fig. 8a). A change point in solar radiation in the Okhotsk region appeared in 1989/1990 in Apr-Jun and in Jul–Sep, and in 1991/92 in the Tokachi region during Apr–Jun (Fig. 8b). A change point in 2000/01 settled a phase of fewer rainy days until 2007/08, when a new breakpoint was observed during Jul–Sep (Fig. 8c and d).

## 4. Discussion

### 4.1. High summer temperature changes potato yield

Increase in summer air temperature was a major driver of potato yield. In our analysis, some discontinuous changing periods were found, which coincide with a general trend of declining yield toward the late 2000s. The change point of average temperature in both region and $T_{max} > 28$ °C in the Tokachi region was 2009/10 in July–September. Furthermore, the change points of $T_{ave} > 15$ °C in Tokachi and Okhotsk regions were 2005/06 and 2006/07, respectively, for July–September.

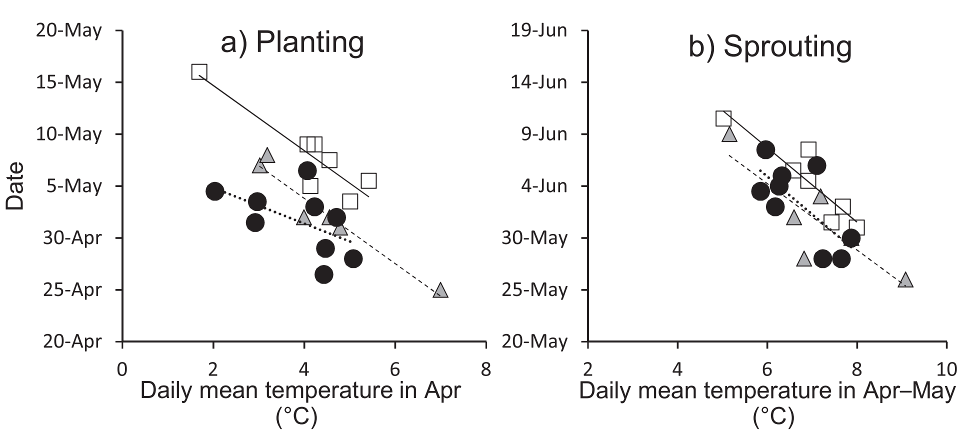


**Fig. 7.** Correlations between a) planting and mean air temperature in April, and b) sprouting and mean air temperature from April to May during the period of 1985–1991, 1995–2000, and 2006–2014 in eastern Hokkaido. Solid, dotted and long dotted lines represent the regression lines between temperatures and planting and sprouting date during the period of 1985–1991, 1995–2000, and 2006–2014.

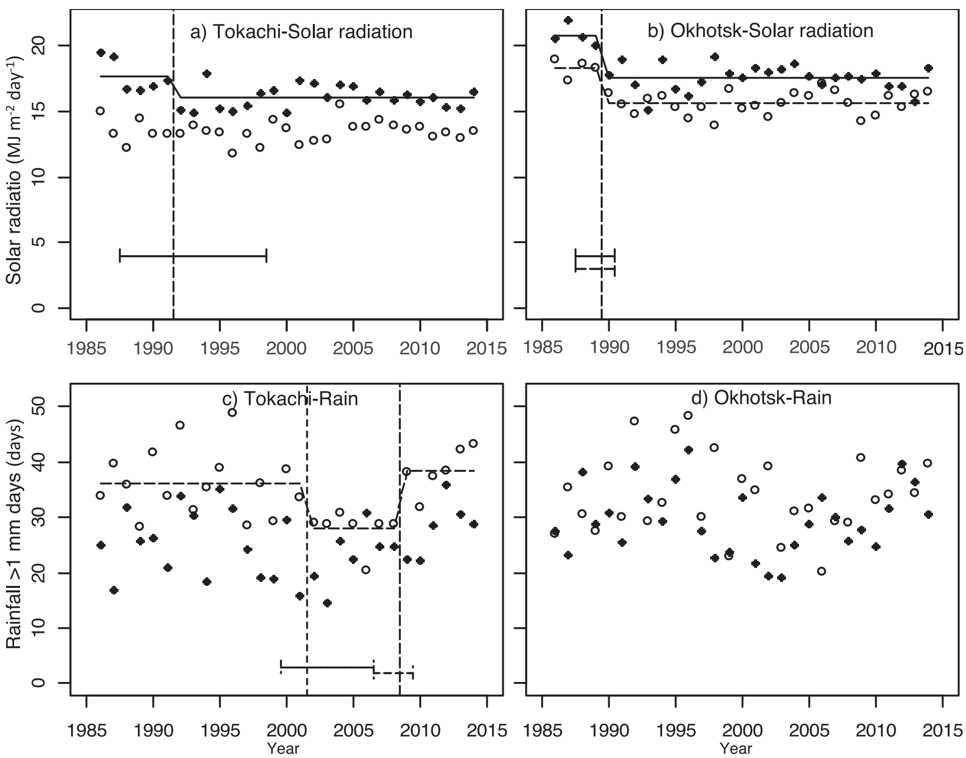


**Fig. 8.** Time series of the solar radiation in a) Tokachi and b) Okhotsk regions and days of rainfall > 1 mm c) Tokachi and d) Okhotsk during Apr–Jun and Jul–Sep. Black and white circles represent plots during Apr–Jun and Jul–Sep, respectively. The horizontal solid and dotted lines represent the mean values for the periods before and after the change point during Apr–Jun and Jul–Sep, respectively. The horizontal solid and dotted bars represent a confidence level of 95% during Apr–Jun and Jul–Sep.

Zhao et al. (2016) reported that current temperatures in northern China are near the limits of potato temperature range, and may be so high as to inhibit or even completely suppress tuber growth. Previous studies have shown that the upper limit of $T_{ave}$ for potato growth is about 23–24 °C (Burton, 1981; Dwelle et al., 1981), whereas $T_{max}$ above 25–30 °C has been found to promote cessation of growth and leaf senescence (Kooman and Haverkort, 1990). A crop growth model using periodical mean temperatures shows that the potential yield in Hokkaido has not noticeably changed over several decades, because higher temperature reduces tuber yield and extends growing period, but the fertilization effect of $CO_2$ compensates yield (Deguchi et al., 2016). However, spatial and temporal mean data for air temperature in the model may ignore the effect of actual extreme fluctuation of daily temperature. Our high-resolution meteorological datasets have improved our understanding of the climatic drivers of yield. Although the mean $T_{ave}$ and $T_{max}$ have been above the upper limit of temperature during most of the period in Hokkaido, temperatures above the optimal range for potato growth increased in recent years.

Yield reduction in the year 2010 was associated with a highly significant negative correlation between April and August temperatures. Monthly air temperature in eastern Hokkaido shows that the contrast between April and August has increased after 2000s, similar to other reports in Japan (Kanno, 2013; Urabe and Maeda, 2014; Hirota et al., 2017). This may be due to La niña mode SST pattern causing stronger Pacific trade winds during a negative IPO period in the year 2000 (England et al., 2014). In the year 2010, the lowest potato yield in Tokachi and Okhotsk regions were due to the high temperatures in summer. Furthermore, the climate pattern after 2000 was limited to warm April with cool August or cool April with hot August. Although the highly significant negative correlation makes it difficult to divide the strength of contribution, high temperature in April or May have a significant positive effect on the yield in the Tokachi and Okhotsk regions. A cool spring delays both planting and sprouting, and a hot summer shortens the growth period, as was the extreme case in 2010.

The climate trend of warm springs with cool summers or cool springs with hot summers may be more likely to change with phases of the IPO in the near future. As recent stabilization of the potato yield in eastern Hokkaido is associated with large-scale climatic teleconnections, it is possible that the sensitivity of yield to weather will change with climate trends in the near future. Further progress in detecting and understanding decadal climatic trends is essential for decisions concerning how to adapt crop management to the effects of climate change.

### 4.2. Effects of spring temperature on crop management and yield

Air temperatures in April to May were one of the major climatic drivers of potato yield. Our one-month-period analysis showed that higher temperatures in April in the Tokachi region and in May in the Okhotsk region had a positive effect on potato yield, although in April and May potatoes have not emerged yet in Hokkaido. A soil temperature of at least 6 °C is necessary for sprout development and emergence from the seed tuber (Bodlaender et al., 1964; Levy and Veilleux, 2007). Therefore, higher spring temperatures can allow early growth of the seed tuber. In the year 1993, air temperatures in Apr–Jun and yield were the highest in the Okhotsk region (Appendix Table A1), which will accelerate both, emergence and growth. Furthermore, frostless snowy winters could enhance early start of the potato management and prolonged growth period due to the early frost-free condition. Soil frost depth has decreased from the late 1980s, because of early snow accumulation and warmer climate during early winter (Hirota et al., 2006), and early snowmelt and thawing rapidly increases soil temperature from the surface down to deeper layers (Iwata et al., 2008). Brown (2013) reported that potato yields in Scotland are sensitive to soil conditions in spring, because wet conditions can hinder access to the fields and crop establishment. Since our results were nearly identical to those in Scotland, we speculate that high temperature in spring can promote early planting of potato throughout snowy countries.

An early start does not necessarily entail a longer a growth period, because sprouting is not dependent on planting time alone. In recent years, potato farmers in Hokkaido have been starting to plant in late April or early May, which is earlier than traditionally, to prevent severe frost damage and mitigate the effect of summer high temperature. We found that the response of planting date to temperature has gradually become earlier in Hokkaido. However, potatoes are damaged by frost after sprouting, which often causes yield loss (Pulatov et al., 2015). The coastal area in the Okhotsk region experienced frost damage in the year 1998 (Itoh et al., 2005) due to early emergence (May 26 in our data) and late spring frost. As observed in the year 1998, this may be associated with an increased risk of frost damage, which causes substantial yield loss in the region. Early planting enhances the risk of frost exposure and subsequent potential damage without time-series increasing spring temperature in the region. In general, the adaptation of cropping systems to climate change provides less sensitive information on the climatic drivers of crop production based on time-series yield data (Licker et al., 2013). However, the past decadal adaptation of cropping systems in potato to climate change is ineffective as a countermeasure to high temperatures in summer, due to the remaining spring frost risk in Hokkaido. A strategic approach will be required to achieve a sustainable planned adaptation, such as developing new frost-tolerant cultivars, although this will be a time-consuming process (Mori et al., 2015). Under global warming, early tillage and planting is considered an important and the most effective farm-scale adaptation to avoid the effects of high summer temperatures during the tuber growth stage in cold regions (Tubiello et al., 2002; Haverkort and Verhagen, 2008). Further change points of spring climate would allow early planting without frost risk of potatoes in Hokkaido, while the promotion of early planting needs to be considered carefully under current conditions.

### *4.3. Effects of other factors on yield*

Other factors affect the potato yield as well. Cultivar was an important driver of change point in potato yield. The first change point in the Okhotsk region was the year 1996, which coincided with the time leading cultivar \`Beninaru\` was replaced by \`Konafubuki\` on a large scale in this region. After the year 1986, starch potato cultivars \`Beninaru\` and \`Konafubuki\` always occupied more than 60% of the cultivation in the Okhotsk region of eastern Hokkaido (Hokkaido, 2016). The old leading cultivar \`Beninaru\` is a higher dry matter and lower starch variety than the new the leading cultivar \`Konafubuki\` (Noda et al., 2004; Deguchi et al., 2016). The shift of a leading cultivar to one that was less productive reduced potato yield in the Okhotsk region in the late 1990s. At this time, the change points of $T_{max} > 28\,^{\circ}C$ and $T_{ave} > 15\,^{\circ}C$ were detected in April–June only in the Okhotsk region. Higher temperature on early growth delays turberization (Lorenzen and Ewing, 1990) and reduces tuber growth (Van Dam et al., 1996). Although we cannot find how a few days at the upper limit of temperature contribute to early potato growth, increase in spring temperature would contribute by extending the growth period. Irrespective of regions, the common change point was in the late 2000s, when there was no drastic change in cultivars. Certainly, although the area of 'Irish cobblar' gradually decreased with time, 'Toyoshiro' cultivar gradually increased with its higher potential for productivity than 'Irish cobblar' (Jitsuyama et al., 2009). We can recognize that cultivar change is not always the main reason for the decrease in yield observed in Hokkaido.

Rainfall is one of important climatic driver for potato yield. Potatoes are sensitive to drought conditions in rain-fed cultivation systems (Deguchi et al., 2015). In many countries, irrigation increases yield in some precipitation-deficient areas, such as the northern European plains, central China, and the eastern part of North America (Haverkort et al., 2013). Our change point analysis for rainfall detected 2001–2007 during July–September as a period of relatively dry conditions in the Tokachi region. Largest yield was recorded in 2002, during the dry period, in the Tokachi region, where potato occupies more than half the area of humid soils. Although solar radiation would be associated with yield potential, the change point of solar radiation near the year 1990 did not correspond with the change in yield. The contribution of solar radiation was lesser than the association of yield with temperature or rainfall.

We suggest that subsoiling is a possible adaptation measure in response to climate changes at a farm-scale. Water logging and saturation are more likely to occur in slowly permeable soils (Daccache et al., 2012). Soil compaction in potato fields has increased in recent decades due to intensive farming practices, including use of heavy machinery (Stalham et al., 2007; Berisso et al., 2012). Agronomic practices such as subsoiling can increase potato root growth for enhanced drainage and nutrient uptake because of improved water penetration (White et al., 2005). As upland crop yield in Fluvisoils can become unpredictable after heavy or prolonged rainfall (Jitsuyama, 2017), this farm-scale adaptation would be effective in the Tokach region, where potato occupies more than half the area of humid soils. Although the climate change projection has much uncertainty for the position, some studies show a possible increase in summer rainfall in Hokkaido in the near future (Inatsu et al., 2015). From a long-term point of view, improvement in drainage is one possible strategy for adaptation to climate change in a humid soil area.

## 5. Conclusion

We focused on the weather conditions that affect potato yield. We showed change points in potato yields and weather by defining 1986 as the border where yield tended to start levelling off. The most important finding was that the recent climate trend of increasing summer temperatures since 1986 and unaltered cool springs has caused potato yield in Hokkaido to level off. $T_{min} < 5$ did not decrease from 1986 to 2014 despite increased $T_{max} > 28$ and $T_{ave} > 15$ beginning in the late 2000s. Farmers try out adaptation measures, such as early planting to avoid the risk of high summer temperature in the region. However, early planting is not effective to promote early sprouting due to the low spring temperatures. Climate pattern after the year 2000 was limited to warm springs with cool summers or cool springs with hot summers. The lowest annual potato yield during the time series, in 2010, was caused by a cool spring followed by a hot summer. Specific seasonal temperatures and low-productivity cultivars have caused potato yields in Hokkaido to fall below those of other countries where potato is a high-yielding crop. To assess the effect of climate change on potato yield, additional aspects of both pre-planting and growing seasons should be considered in Hokkaido and other snowy zones. Our results suggest that on a farm-scale, improvement of drainage by subsoiling in humid soils and detection of decadal climate shift can effectively help adaptation of the potato crop to climate change.

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## Appendix A

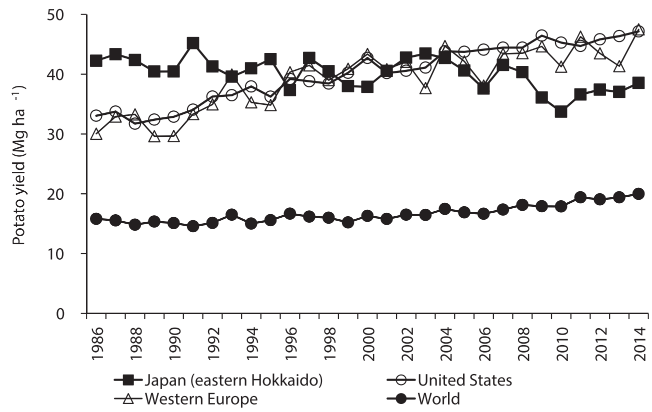


**Fig. A1.** Changes in annual potato yield in eastern Hokkaido, the United States, Western Europe, and world average. Data source: FAO, Accessed 1 Feb 2017.

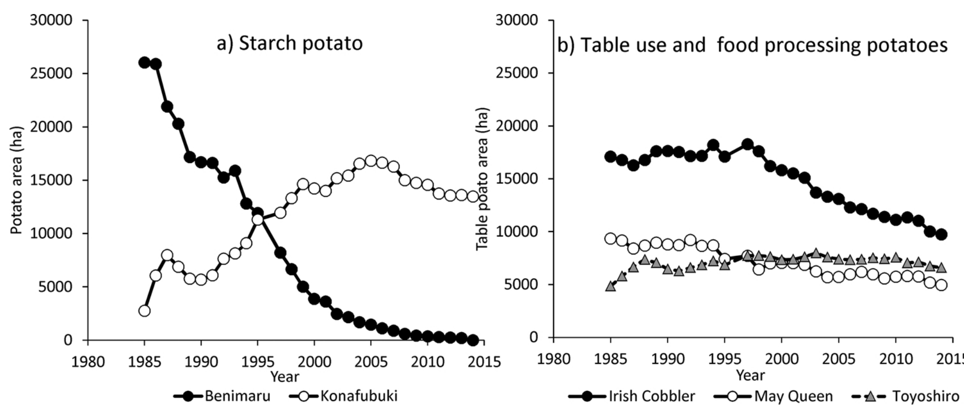


**Fig. A2.** Changes in annual potato area of major cultivars in eastern Hokkaido. Data source: Hokkaido, Accessed 1 Feb 2017.

**Table A1**
Soil types in Tokachi and Okhotsk regions. Data source: Hokkaido.

| Soil type | Area (%) | |
|---|---|---|
| (FAO/UNESCO) | Tokachi | Okhotsk |
| Andisols | 32.2 | 22.8 |
| Dystric Cambisols | 7.7 | 27.5 |
| Glaysols | 5.5 | 14.6 |
| Fluvisols | 50.7 | 30.2 |
| Fibric Histosols | 4.0 | 4.0 |
| Other | 0 | 0.8 |

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