Projected changes in field workability of agricultural machinery operations for upland crop production with +4 K warming in Hokkaido, Japan

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Abstract

The use of agricultural machines for field operations is often restricted by the soil status, which is determined by the meteorological conditions several days before the operation. While a projected rise in air temperature caused by climate change may promote evapotranspiration and incur positive impacts on the use of agricultural machines, intensified rainfall may have negative effects. Here, we provide probabilistic estimates of climate change impacts on meteorological constraints on the field workability of agricultural machines in Hokkaido, Japan. Analyses based on historical meteorological data and machinery operation logs recorded at two agricultural research stations revealed that operations were concentrated on days with a smaller antecedent precipitation index (API). A simple derivative that reflects a maximum API value for conducting a certain field operation, termed threshold API, was proposed to evaluate meteorological constraints on field operations. The threshold API values for operations that were vulnerable to soil conditions such as seeding or seedbed preparation, and/or in fields with poor drainage soil were small; therefore, this threshold should be a reasonable and quantitative measure of the meteorological constraint on field workability. Using 1 km gridded API values under historical and future climates calculated from a large ensemble dataset of daily mean air temperature and precipitation, we separated workable and unworkable days from June to October based on a threshold value of 5 mm and calculated changes in the monthly numbers of total workable days and consecutive unworkable days. While there were slight negative effects in several of the southern and central regions under a 4-K warmer future climate, positive changes prevailed in the total workable days and consecutive unworkable days in the other regions and months. The present results facilitate a probabilistic discussion of changes in agricultural calendars and suggest that climate change may extend the agricultural season in Hokkaido.

Key words: Antecedent precipitation index, Climate change, d4PDF, Evapotranspiration

1. Introduction

Crop productivity highly depends on the use of agricultural machinery for various purposes, including soil preparation (e.g., tillage and leveling), seeding, and harvesting. Although ideally each operation should be performed within a suitable time window, meteorological conditions often impose rescheduling to avoid topsoil compaction and vehicles lodging in the soil. Even if the soil condition is physically suitable for a tractor to step in (i.e. tractionable, trafficable, or tractable), other operations, such as seeding or seedbed preparation, cannot be performed (i.e. not workable) to avoid damage or disturbance to the soil or plant, which often hinder subsequent operations. Note that the terms ‘tractability’, ‘tractionability’, ‘trafficability’, and ‘workability’ have indicated different concepts or have been used interchangeably as mentioned by Rounsevell (1993). In the present article, we separate physical tractability and practical workability and focus on the latter, referring to a workable day as a ‘workday’ and a non-workable day as an ‘unworkday’. Earlier studies used soil water status to analyze climatic constraints on field operations, as intensively reviewed by Rounsevell (1993). In Canada, the soil water status is often estimated using the Versatile Soil Moisture Budget model (Baier and Robertson, 1966). Rutledge and McHardy (1968) analyzed the relationship between soil moisture content and field tractability for tillage operations in Alberta and reported that tractability was reasonably estimated based on the soil water content of two or three surface layers. Chipanshi et al. (2018) performed a spatial assessment of field trafficability based on the soil water content of the upper 5 cm depth in the Canadian Prairies. The soil water content of several surface layers has also been used to assess the commencement of spring field operations (Selirio and Brown,
1972; Bootsma and de Jong, 1988). In their study on maize in southwestern France, Maton et al. (2007) proposed a model that calculated suitable days for sowing by combining an estimation of soil trafficability determined from the ratio between the soil water content and the field capacity, and modules to estimate soil frost occurrence and to attain a cumulative temperature required for normal development. Based on long-term monitoring of the soil water content and soil mechanical strength at six field sites in Europe, Earl (1997) developed a model for predicting the number of trafficable and workable days from the soil water deficit for each soil type.

The antecedent precipitation index (API) is another variable used to assess field workability. This variable represents soil water content (in mm) and is calculated from meteorological variables without, or with a few, soil parameters (see also Eqn. 1). API calculations require little computational resources, and they are particularly suitable for large-scale spatiotemporal analyses. McFarland and Beach (1981) used API to develop an equation to judge whether a given day is tractionable. By calculating growth season API values in sugar beet fields, Kominami (2016) discussed the API effects on various operations including soil preparation and transplantation in spring, and weeding and spraying in summer. This author reported that the API constraint on the operation differed among the categories of and suggested the usefulness of the API in predicting the availability of agricultural machines for various operations. While most of the aforementioned studies focused on a certain category of operation, the constraint should be dependent on the categories of the operation, as suggested by several earlier studies (McFarland and Beach, 1981; Kominami, 2016). For example, seeding with a grain drill and seedbed preparation should be more vulnerable to wet soil conditions than harvesting with a combined harvester. Meteorological constraints on the use of agricultural machines should be determined and discussed in terms of specific operations.

Meteorological constraints on field operations with agricultural machines will be modified due to the climate changes in temperature and precipitation (IPCC, 2021). A projected rise in air temperature will promote soil drying, implying a positive effect on the use of agricultural machines. However, it has been projected that global precipitation will increase in the future, which can reduce workdays. These contrasting effects on field workability should be quantified to implement adaptive measures against potential risks to agricultural systems. Rousevell and Brignall (1994) performed a sensitivity analysis for England and Wales, focusing on the autumn tillage operation, and reported that an increase in the workday induced by 2 K warming could be offset by an increase in precipitation of 10%. Brown (2017) mapped variations in constraints on agriculture imposed by waterlogged soil in 1961–1980, 1991–2010, and predictions for the 2050s based on a single climate model (HadRM3 / HadCM3) over Scotland. This author assessed the constraints based on an index calculated from topsoil water retention properties and depth to a slowly permeable layer and reported that a long-term shift toward drier conditions could reduce the risks. However, because projected changes in temperature and precipitation exhibit significant spatiotemporal variations (Collins et al., 2013), this result should not be generalized. For example, Tomasek et al. (2017) simulated the number of workdays in nine Illinois districts under a future climate based on three IPCC AR4’s emissions scenarios (B1, A1B, A2). They reported an increase in the numbers from late March to early April across all scenarios, with an overall decline from April through May. A similar seasonal gap in projected changes in the workdays has been reported in Scotland (Cooper et al., 1997). Moreover, climate models also suggest an intensification in rainfall patterns, whereby total rainfall per event will increase, while the number of days with rainfall will decrease (IPCC, 2021), implying greater year-to-year and within-year fluctuations in workability. Probabilistic risk assessments based on a multi-model ensemble climate dataset are necessary to mediate this interannual variability.

This study focused on Hokkaido, the northernmost of the main islands of Japan, and aimed (1) to analyze meteorological constraints on agricultural machine operations in upland fields and their dependency on field operations categories and soil characteristics using historical meteorological data and available records of machine usage, and (2) to quantify projected changes in risks of the use of agricultural machines based on a relationship deduced from the preceding analysis. The study domain is a dominant production area of upland crops (e.g., wheat, potato, and sugar beet) in Japan that operates as a large-scale farming system dependent on agricultural machines. To assess the relationship under future climate scenarios, we used the large ensemble climate dataset called ‘Database for Policy Decision-Making for Future Climate Change’ (d4PDF; Mizuta et al., 2017; Fujita et al., 2019). This dataset offers probability density functions for meteorological variables and their derivatives, which allow us to probabilistically discuss their changes in averages and extremes.

2. Materials and methods

2.1 Dataset

We used three datasets in this study: records of machine usage, historical meteorological data based on observations, and meteorological ensemble data under historical and future climates. All analyses and data handling were performed using the statistical software R (R Core Team, 2019; ver. 3.6.2).

We collected records of machine usage records at two research stations, Sapporo and Memuro (Fig. 1), of Hokkaido Agricultural Research Center, National Agriculture and Food Research Organization (NAO). The records consisted of information about the date, duration and category of the operation, location of the field, plants cultivated, and other data. We extracted records of operations in upland crop fields at the research stations by removing records from paddy fields, grasslands, and fields outside of the research stations. The number of valid records from June to October was 1,604 for the Sapporo station (2009–2019) and 4,345 for the Memuro station (2003–2019). The fields of the Sapporo stations are usually covered by a volcanic ash-derived Andosol (0–30 cm) with a less permeable alluvial layer underneath, whereas the effective soil layer of the Memuro fields is a well-drained volcanic ash-derived Andosol.

We sourced the Agro-Meteorological Grid-Square Data System (AMGSDS; Ohno et al., 2016) to collect historical
meteorological data at the stations. This dataset offers daily meteorological elements, elevations, and land-use classifications with a grid spacing of approximately 1 km. Values were produced by the interpolation of observations at weather stations operated by the Japan Meteorological Agency with an average interval of approximately 20 km. The mean values of 16 grid cells around the stations (−4 km × 4 km) were subjected to the analyses.

To determine the meteorological constraints on the use of agricultural machines in historical and future climates, we used d4PDF (Mizuta et al., 2017; Fujita et al., 2019). This dataset consists of three sets of experiments: a historical climate experiment from 1950 to 2010 (hereafter HIST), a +2 K future climate experiment (+2 K, equivalent to 2040 in the RCP8.5 scenario), and a +4 K future climate experiment (+4 K, equivalent to 2100 in the RCP8.5 scenario) relative to the pre-industrial era. 2-m air temperature and precipitation data of d4PDF were interpolated from 20 km × 20 km to 1 km × 1 km using an inverse distance weighting method with a power factor of three (Murakami et al., 2022). Biases in the interpolated values were corrected using a method based on the cumulative distribution function (Iizumi et al., 2010) with AMGSDS data as references. Bias correction was performed for every grid cell and using a 10 d window (i.e., from 1 to 10, from 11 to 20, and from 21 to the end of the month) (Murakami et al., 2022). Thirty ensemble members from the HIST, +2 K, and +4 K experiments were used for the analyses. As each member has daily data for 30 years, the total simulations were 900 years for the respective experiments. Projected changes in precipitation exhibited remarkable spatial variation (Fig. 1c): a substantial increase in plain areas of the southern and central regions (Sites i and vi), a slight increase in the eastern region facing the Pacific Ocean (Sites vii and viii), and little changes in the northern and Okhotsk regions (Sites iii and iv). There were a few regions including the Ishikari Plain around Sapporo (Site ii) and the plain around Hakodate (Site v) where the projected change was negative. In contrast, the projected changes in mean air temperature were relatively uniform, except in the central mountain area (Fig. 1b).

### 2.2 Calculation of API and its derivative

From the daily meteorological data of AMGSDS and d4PDF, we calculated API on day $i + 1$ according to Hirota and Fukumoto (2009) with a slight modification, as follows:

$$ API_{i+1} = a_i (API_i + Pr_i), $$

$$ a_i = \exp \left( \frac{-Ep_i}{Pr_i} \right), $$

where $Pr_i$ is daily precipitation on day $i$ [mm], $Ep_i$ is potential evaporation [mm] on day $i$, $a_i$ is the recession coefficient, and $Pr_i$ is an evaporation depth [mm] empirically fixed at 10 mm.

From an initial API value of zero on May 1, the daily API values were calculated sequentially until October 31. API values in May were not subjected to analyses, or regarded as a spin-up period, to remove the influence of snowmelt water. The snowmelt period is approximately from mid-March to mid-April in the present study domain. The daily $Ep_i$ values were calculated using the ET.McGuinnessBordne function implemented in the R package Evapotranspiration (Guo et al., 2016) as follows:

$$ Ep_i = \frac{S_0 (T_{aw} + 5)}{68 \cdot \lambda}, $$

$$ S_0 = \frac{60 \cdot 24 \cdot G_{aw}}{\pi} d_i (\omega_i \sin \phi \sin \delta + \cos \phi \cos \sin \omega_i), $$

$$ d_i = 1 + 0.033 \cos \left( \frac{2\pi}{365} J \right), $$

$$ \omega_i = \arccos (\tan \theta \tan \delta), $$

$$ \delta = 0.409 \sin \left( \frac{2\pi}{365} J - 1.39 \right), $$

Fig. 1. (a) Contour map of Hokkaido based on altitude data at a grid spacing of ~1 km, increases in (b) mean air temperature [°C] and (c) total precipitation [mm] under +4 K climate compared to the historical climate from June to October. Insets show probability density functions of meteorological elements under historical (gray), +2 K (orange), and +4 K (red) climates at eight representative sites. Gray thin lines show municipal boundaries. The boundaries are published by National Land Information Division, National Spatial Planning and Regional Policy Bureau (https://nlftp.mlit.go.jp/ksj/index.html, accessed on 2021-04-06).
where $T_{ai}$ is the daily mean air temperature on day $i \, [\degree C]$, $\lambda$ is the latent heat of vaporization (2.45 MJ kg$^{-1}$), $S_0$ is the extraterrestrial radiation [W m$^{-2}$], $G_{sc}$ is the global solar constant (0.0820 MJ m$^{-2}$ min$^{-1}$), $d_r$ is the inverse relative distance between Earth and Sun [dimensionless], $\sigma$ is the hour angle at sunrise or sunset [rad], $\phi$ is the site latitude [rad], $\delta$ is the sun declination [rad], and $J$ is the Julian day number.

To confirm that API values tended to be low on workdays and high on unworkdays, histograms of API on days with or without field operations at Sapporo station (2009–2019) and Memuro station (2003–2019) were compared. For quantitative comparison, the API values were fitted to exponential distributions with a rate parameter $z$, that is, $y = z \exp(-z x)$. A greater $z$ indicates that the API value is distributed around zero, and the API histogram has a sharp shape.

We here defined a threshold API ($API_{th}$) as follows:

$$API_{th} = \arg\max_k \left\{ \frac{N}{100} \sum T \geq \sum_{API \leq k} T \right\},$$

where $T$ is the work duration of each record on an hourly basis. The $API_{th}$ indicates that $N \%$ of the total work duration was concentrated on days with an API lower than this threshold. A lower $API_{th}$ value indicates that the operation is vulnerable to wetter conditions. The $API_{th}$ values were calculated using the records of machine usage and historical API values derived from AMGSDS data. We adopted the third quartile (75%) as the criterion for discussing workability. From the determined $API_{75}$ value and simulated API values based on the d4PDF dataset under historical and future climates, we discussed machine workability at a grid spacing of approximately 1 km. To compare constraints in different categories of field operations, we pooled data from both stations and calculated the $API_{75}$ for three different categories: seeding, soil preparation, and harvesting. To compare constraints in different soil types, we pooled data of all categories and calculated the $API_{75}$ for the two stations. Although the threshold API value could differ depending on other factors (e.g., plant species and cultivation systems), we did not analyze their effects because of the limited sample size of dataset.

### 3. Results

#### 3.1 Effects of API on the use of agricultural machines

Histograms of API values on days with or without field operations from June to October were approximated by the

![Fig. 2. Histograms of antecedent precipitation index (API) on days (a) with or (b) without field operations at Sapporo station (2009–2019) and Memuro station (2003–2019). Lines are normalized exponential distributions with a parameter lambda estimated by fitting with the histograms.](image-url)
exponential distributions (Fig. 2). Compared to the histogram of API on days without operations, the histogram of workdays decreased sharply in response to an increase in API as characterized by a greater value of \( z \) (the rate parameter of exponential distribution). This result suggests that the operations avoided days with high API values (i.e., wet soil conditions) and were selectively aggregated on days with lower API values (i.e., drier soil conditions).

The API\(_{75}^\) values for sowing (6.7 mm) and soil preparation (8.1 mm) were lower than that for harvesting (11.9 mm) (Fig. 3). The API\(_{75}^\) values for all operations at Sapporo station (6.0 mm) were lower than those at Memuro station (9.4 mm) (Fig. 4). These results suggest that meteorological constraints on the use of agricultural machines depend on both the category and site of operation. Since a lower threshold API indicates a strict limitation, operations for sowing and at Sapporo station presumably require several dry days prior to the operations.

3.2 Effects of climate change and their constraints on agricultural machine operations

We separated workdays and unworkdays with a fixed threshold API of 5 mm, which was determined for the most severe operation (sowing at Sapporo station; data not shown). Compared to the monthly number of workdays in the HIST experiment, the projected numbers were greater under the +2 K and +4 K experiments (Figs. 5, and S1). In addition to the substantial increases in workdays at mountains with high elevations (Fig. 1a), the number of workdays increased in most sites and months in agricultural fields. For example, in October, currently unworkable in most regions, the number of workdays was projected to increase by more than one week in some regions, including the eastern regions (Kitami (iv), Memuro (vii), and Kushiro (viii)) and near Sapporo (ii). However, this number was not projected to increase in all regions. The increase was not clearer in the western regions on the Pacific side, such as Muroran (vi) and the central region around Asahikawa (i). In August, this number was projected to decrease at several sites in these regions.

In addition to the total number of workdays, consecutive unworkdays constitute another index of interest. Consecutive unworkdays often delay farming plans and spoil the crop quality. Climate change is expected to intensify rainfall (IPCC, 2021); therefore, it is possible that heavier rainfall events will cause continuously high API days under future climate conditions. To

**Fig. 3.** Stacked total work durations as a function of antecedent precipitation index API for different categories of field operations, (a) seeding, (b) soil preparation, and (c) harvesting. 75 % of operations on an hour basis are conducted on days with an API value less than the threshold API (vertical lines).
quantitatively assess this hypothesis, we estimated the monthly maximum value of consecutive unworkdays over Hokkaido (Figs. 6, and S2). Similar to the total number of workdays, consecutive unworkdays decreased in most regions and months, particularly in the eastern regions and in September and October. Negative effects were found only in small sites in the western regions on the Pacific side in August and September, and in the central region around Asahikawa in July and August.

4. Discussion

4.1 Threshold API as a measure to assess the workability of agricultural machines

To determine whether a threshold API is valid for separating workdays and unworkdays, we analyzed and compared the API values for each operation category and research station. Workdays for harvesting were mainly determined by the plant growth rather than meteorological constraints because shifting the harvest date forward and backward often deteriorates product quality. For other operations, such as seeding and soil preparation, a slight change in the schedule has less impacts on productivity, and the workability was essentially dependent on the soil conditions, leading to lower threshold API values than harvesting. Similarly, the difference in the soil drainage properties may explain the lower threshold API value at Sapporo station compared to that at Memuro station. Most Memuro fields are well-drained, whereas less permeable layers with poor drainage are found beneath the surface layer in the Sapporo fields. Researchers and operators who have experienced both stations know that operations can be conducted on the day after a substantial rainfall in Memuro, but not in Sapporo (personal communication). These analyses of the relationships between threshold API values and constraints on the workability of agricultural machines confirmed that, as expected from the theoretical equation (Eqn. 8), a lower threshold API is found in operation categories that are severely limited by field conditions or in fields that are known to be poorly drained. Therefore, the threshold API should be a useful index for assessing field workability under future climate conditions, as discussed in the following section.

4.2 Projected changes in the workability of agricultural machines under +4 K climate

For the probabilistic assessment of the availability of agricultural machines under historical and future climates, we calculated the daily API values under the HIST, +2 K, and +4 K experiments using the d4PDF dataset. In the present simulation, workdays and unworkdays were separated using a fixed threshold API of 5 mm. This discrimination may underestimate the

![Graphs](https://example.com/graph.png)

**Fig. 4.** Same as Fig. 3 for values for different regions, (a) Sapporo and (b) Memuro.
workability because some operations appeared to be available on days with API values higher than this value (Figs. 2, 3, and 4). In general, climate change may have positive effects in terms of soil moisture on the use and availability of agricultural machines (Figs. 5, and 6), as it was reported in Scotland (Brown, 2017). These preferable changes are mainly attributable to rises in the air temperatures (Fig. 1b), which facilitate rapid decreases in API owing to enhanced evaporation. However, in the southern regions around Muroran and Hidaka and the central regions around Asahikawa, we detected negative effects of climate change (Figs. 5, 6, S1, and S2). These negative changes were attributable to the projected increase in precipitation in these regions (Fig. 1c). While potential risks in the use of agricultural machines were suggested, negative changes in the number of the total workdays and the consecutive unworkdays were small (< 1 d per month), and negligible in the present study domain without changes to the agricultural calendar. Although global 4 K warming was projected to induce a rise in air temperature of ~ 5 K (Fig. 1b) and specific humidity of ~ 35 % in summer in Hokkaido following the Clausius-Clapeyron relationship—a temperature rise of 1 K would increase the water vapor mixing ratio by approximately 7 % if the relative humidity remained at the present level, the projected increase in precipitation was less than this level due to changes in patterns of synoptic circulation phenomena around Japan.

![Fig. 5. Changes in number of monthly workable days [d] under +4 K climate compared to historical climate in (a) August and (b) October. Insets show probability mass functions of numbers of workable days under historical (gray), +2 K (orange), and +4 K (red) climates at eight sites.](image)

![Fig. 6. Same as Fig. 3 for changes in the number of monthly maximum consecutive unworkable days [d].](image)
Takabatake and Inatsu (2022) reported that summertime precipitation under a +4 K climate decreased by 10–20 % almost over central Japan, but increased in western Kyushu (southern- and westernmost of the main islands of Japan) by 20–30 %. The use of agricultural machines during summer may be less affected by climate change in most Japanese regions, including the main island and Hokkaido, but it can be vulnerable to climate change in western Kyushu.

**4.3 Limitations of the present study**

A change in the agricultural calendar may be required in response to climate change. For example, warmer winters can accelerate the snowmelt season and allow earlier spring seeding and planting of some crops (Katsuyama et al., 2020). This can be an effective adaptive measure to global warming because it 1) deaccelerates the growth and developmental rates and guaranteeing a longer growth period, and 2) avoids growth retardation in hot summers caused by the suppression of photosynthesis. Recent studies analyzed the relationship between historical yields and planting/seedling dates and found positive effects of early planting/seedling on crop yields (e.g., Baum et al., 2020) whereas some studies reported that early planting/seedling may not be effective (Shimoda et al., 2018; Shimoda and Hamasaki, 2021; Sugawara et al., 2021). The field workability of a certain operation should be calculated based on an agricultural calendar in the present climate and shifted one to a future climate to facilitate a more practical approach for discussing the effects of climate change on the use of agricultural machines.

Another limitation related to the soil characteristics. The types and physical properties of soils should be related to both drainage and evaporation. While we detected a difference in the threshold API at the two sites, which should be attributable to the soil characteristics (Fig. 4), the present model did not implement soil data, unlike previous studies (e.g., Brown, 2017; Chipanshi et al., 2018). The soil characteristics often differ, even among neighboring fields, depending on cultivation history and soil management. A practical system to support decision-making should requires fine parameterizations, perhaps at the level of respective parcels.

Eqn. 1 was developed for simulations of bare soil (Hirot a and Fukumoto, 2009) and was not designed to discuss the snow surface. Although the early and timely commencement of spring field operations is believed to be essential for productivity in Hokkaido, we were not able to estimate the constraints on spring operations immediately after snowmelt due to the model limitation. As meteorological constraints on workability are the most severe in this season due to the abundance of snowmelt water, further study is required to develop a method that identifies workable spring days from meteorological data.

**4.4 Concluding remarks**

Meteorological constraints on agricultural machine operations in fields were analyzed in combination with operation records at research stations and historical meteorological data. We determined threshold API values, upper limit API values that were suitable for given operations, and verified that the index effectively reflected the availability of agricultural machine operations. Based on the threshold and calculated API values using a large ensemble dataset of daily meteorological data under historical and future climates, we quantified the monthly numbers of total workdays and consecutive unworkdays. Our simulation suggests that climate change decreases and increases total workday and consecutive unworkdays at a few sites in the southern and central regions of Hokkaido during the summer. In the other regions, in contrast, climate change has positive effects on workability of agricultural machines in both metrics.

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