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# Different responses to weather events may change the cultivation balance of spring barley and oats in the future

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ABSTRACT

The major elements determining the yield potential of crops during the growing period are temperatures and precipitation patterns. In this study, the effects of temperature and precipitation at key growth phases on yield formation of oats (*Avena sativa* L.) and barley (*Hordeum vulgare* L.) were compared using the Finnish official variety trial data (VCU, Value for Cultivation and Use) and farm data (FD) for the period from 1976 to 2018. We examined data of the early growth (0–28 days after sowing), determination of grain number (0–21 days before heading), early grain filling (0–21 days after heading) and the whole growing period. The average yield potential of oats was 300–370 kg $ha^{-1}$ higher than that of barley until the turn of the century. Since 2007, the yield of barley has been on average 376 kg $ha^{-1}$ higher than that of oats (VCU data). In FD, the yield advantage of barley was evident 10 years earlier (starting from 1997). In the VCU data, there were few major differences in the yield potentials of oats and barley due to different weather events, but when significant differences occurred, they were in favor of oats. In practical farming (FD), the yields of barley were slightly but significantly higher than those of oats in most studied weather events. Oat yields were higher in the FD only when high precipitation occurred during early grain filling or on average during the whole growing period. The results indicate that the predicted higher precipitation and the increased risk of heavy rain events in the future warmer climate will threaten barley production more than oats, unless new flood tolerant varieties are introduced. Early sowing and cool early growth periods are beneficial to both crops. Barley is more sensitive than oats to delayed sowing and to an increase in the temperatures during early growth. During the periods of grain number determination and early grain filling, low temperatures resulted in significantly higher yields in oats than in barley in the VCU data, but at higher temperatures this difference disappeared. This indicates similar tolerance of slight temperature increases in both crops at these growth phases. Temperatures above 28 °C during the time frame of anthesis decreased the yields of both crops, with oat yields decreasing more than those of barley. This calls for introduction of new, heat tolerant varieties of both crops, but especially of oats, in the warmer future climate. When the growing period was longer than average or when the precipitation during the growing season was high, barley yields were significantly lower than those of oats in the VCU data and about equal to oats in the FD. Low and medium precipitation levels resulted in no differences in the yields of the two crops in any of the studied growth stages in the VCU data. This contradicts the assumption that oats need more water for yield formation than barley. Climate change will challenge crop production in Finland and globally. Availability of nationally and locally suitable crop varieties will help farmers to prepare and respond to climate change.

## 1. Introduction

Oats (*Avena sativa* L.) and barley (*Hordeum vulgare* L.) are the most common cereals grown in Finland. During the past 100 years the cultivation area of oats has decreased from 500 000 to about 300 000 ha and that of barley increased from 100 000 to about 500 000 ha (https://stat.luke.fi/en/, Fig. 1). One reason for the increased area of barley is its suitability for cultivation in most of Finland because of its short growing time and low demand for accumulated daily mean temperatures over +5 °C during the growing season (effective temperature sum, $T_{sum}$) (Peltonen-Sainio and Jauhiainen, 2014). Another reason is the trebling of the volume of pig farming in Finland during the period from 1960 to 1980. Barley is considered a good feed for pigs, and thereby more area was needed for its cultivation (Partala, 2010). Furthermore, in the

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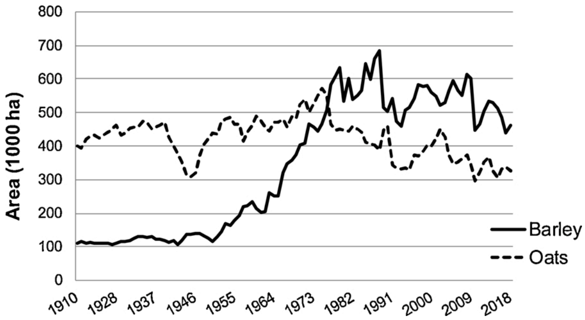


**Fig. 1.** The cultivation area (1000 ha) of barley and oats in Finland from 1910 to 2018 (https://stat.luke.fi/en/).

Nordic region, the breeding of barley has been more active than that of oats. This has produced a wider range of barley varieties to choose from for specific farm conditions (Laine et al., 2017). Over the last decade, 180 new cultivars or breeding lines of barley have been tested in the official variety trials (VCU, Value for Cultivation and Use). As a result, 80 new varieties have been approved for cultivation. Meanwhile, only 76 cultivars and breeding lines of oats have been tested and 38 new varieties approved on the national list of crop varieties in Finland (Finnish Plant Variety Journal, 2018).

The reason for the decreased interest in the cultivation of oats since the 1970's is the decreased use of fodder oats after horses lost importance in agriculture (Partala, 2010). However, oats are still grown in most parts of Finland, despite its higher $T_{sum}$ requirement compared to barley (Peltonen-Sainio and Jauhiainen, 2014). The interest in oats as a part of human diet has been increasing because of its health benefits and the increased demand for vegan and non-dairy products (Rasane et al., 2015). Oats are also suitable for gluten-free diets (Kaukinen et al., 2013; Rasane et al., 2015). The recognition of the qualities/value of oats in human nutrition has already led to increased interest in its cultivation.

Breeding has improved the production potential of all spring cereals. The annual increase in yield potential has been 0.41 % in oats, 0.64 % in barley and over 1 % in spring wheat (*Triticum aestivum* L.) (Öfversten et al., 2004). Even though the genetic potential of spring wheat has increased even more than that of barley and oats, its cultivation area has fluctuated between just 110 000 and 220 000 ha during the last two decades (https://stat.luke.fi/en/). After a peak 232 000 ha in 2014, its area has been decreasing again, probably due to its high $T_{sum}$ requirement (Peltonen-Sainio and Jauhiainen, 2014), which makes it less reliable than other spring cereals in most regions of Finland.

The warming of climate may open new possibilities for production of spring wheat and winter cereals, especially in the northern areas (Elsgaard et al., 2012; Peltonen-Sainio et al., 2009). The production conditions of barley and oats may also improve in the northern Finland, but at the same time the growing conditions in their present production areas may become less favorable (Elsgaard et al., 2012). Together with the increase in temperatures during the growing season in general, the length and severity of heat waves and drought periods and the frequency of other extreme events such as heavy rains are expected to increase with climate change (IPCC et al., 2012). This will challenge crop production in Finland as well as globally. Already at present, excess water or drought at the start of growth, heat waves after heading and increased temperatures during different growth phases have been found to decrease the yields of most barley varieties in Finland (Hakala et al., 2012). If the global temperatures increase by more than 4 °C, the crop production conditions are expected to turn unfavorable in such a way that yields of spring cereals like barley could collapse totally in Finland (Rötter et al., 2011). However, plant breeding is expected to produce new cultivars of spring cereals and other crops with higher tolerance to heat and drought. Adaptation of agronomic practices such as adjusting sowing time and fertilization according to cultivar traits and yield potential will also help to provide ways to continue spring cereal production in Finland (Rötter et al., 2011).

Since 1995, the yields of all the spring cereals - wheat, barley and oats - have stagnated in practical farming at about 3000−4000 kg ha$^{-1}$, despite the increase in the genetic yield potential measured in the VCU trials (Peltonen-Sainio et al., 2015b). The reason for the unrealized yield potential may be the changed management practices after Finland joined the EU in 1995 and the Finnish agri-environmental policy was launched. Farmers have been forced to lower the input levels also because of financial reasons. Grain prices have more than halved since 1995, but prices of several inputs, such as energy and fertilizers have doubled or even tripled, especially after the year 2000 (https://stat.luke.fi/en/).

Oat yields have stagnated at the lowest level of all spring cereals, at about 3000 kg ha$^{-1}$ (Peltonen-Sainio et al., 2015b). Oats have the reputation of being a more modest cereal than barley and yielding better than barley when soil conditions are unfavorable (Bebawi and Naylor, 1978; Mukula and Rantanen, 1989c). However, it has been believed to need more water for yield formation than barley (Chmielewski and Köhn, 1999; Geisler, 1970; Martin et al., 2001; Peltonen, 1990a; Peltonen-Sainio et al., 2011; Shantz and Piemeisel, 1927; Walter, 1962), although valid observations to verify this concept are lacking from the published literature. Barley is known to be demanding for soil conditions and react readily to both excess and deficit in moisture. Both drought and extreme wetness, especially in early season, have been found detrimental to barley yield (Hakala et al., 2012; Mukula and Rantanen, 1989b; Rajala et al., 2011). Oats have been found less sensitive to early season drought than barley, but even more sensitive to early season wetness (Mukula and Rantanen, 1989a, 1989b, 1989c). However, the latter is not corroborated by the general perception, according to which especially barley fields turn yellow even at a slight disturbance in soil water balance.

During the last 100 years, oats and barley have consolidated their position as alternative crops for fodder, but also as vital for human nutrition. If the nutrition value of oats in human diet should lead to significant increase in its cultivation area, the increase would probably displace barley rather than any other crop. The aim of the present study was to estimate how oats and barley have reacted to different weather events related to ambient temperatures and precipitation in the recent past, and how these weather events may affect their yields and alter the preferences of their cultivation in the future with climate change. We studied the effects of weather events on the production potential of oats and barley in general and during the sensitive development stages of the crops, during the period from 1976 to 2018. We selected the data of the VCU tests which had been performed in the same soil and management conditions and then combined the yields with the weather data of the same periods. To discover if the differences which were found between oats and barley in the VCU data have been realized also in the large scale cultivation in Finland, we analyzed the responses of oats and barley to weather in a representative (ca 7 % of total) sample of Finnish farms (FD) during the same period (1976−2018).

Sunlight provides the energy for photosynthesis, biomass growth and yield formation in crops. However, in the present study it was not possible to directly test its effect on yield levels, as the network of radiation measurements by the Finnish Meteorological Institute is insufficient unlike the network of temperature and precipitation measurements. The effects of solar radiation on yields of oats and barley are therefore discussed on the basis of the published literature.

## 2. Materials and methods

### 2.1. VCU yield data

The long-term official variety trials for determining the Value for Cultivation and Use (VCU) have been conducted from 1970 to 2018 at 29 locations (experimental sites) across Finland. Natural Resources

Institute Finland (Luke, former MTT Agrifood Research Finland) has been responsible for arranging the trials, which have followed the procedures specified by Laine et al. (2017). In addition to Luke's regional research stations, some of the trials have been organized by plant breeding companies and private agricultural research stations. The set of experimental sites has varied during the past 50 years. However, some sites have covered the whole 50-year period. In the present study, the sites which had less than 4 years of trials were removed from the final data. Because of the standardization of the experiments, the temporal and spatial distribution of the trials enabled us to obtain reliable estimates of the responses of crops to different weather conditions.

During the 50 years of the VCU, the testing procedures changed only slightly. All experiments were arranged as randomized complete block designs or incomplete block designs in three to four replicates. The tested set of cultivars and breeding lines changed each year, but some cultivars, so called check-cultivars, were included for even longer than 10 years in the testing program. Annual turnover of cultivars and breeding lines was usually less than 20 %, which made it possible to separate effects of environment and genotype (Searle, 1987). The individual plots were 1.25 m wide and 7–10 m long, depending on the location and year. Seeding rate depended on crop, conforming to the commonly used seeding rates in Finland (oats 500–550 viable seeds $m^{-2}$, barley 450–550 viable seeds $m^{-2}$). Weeds were chemically controlled with common herbicides of each time period. Diseases were not routinely controlled with fungicides, but seed treatment has been used in trials since 2010. The absence of pathogen control in field trials was necessary for estimation of the disease resistance of the varieties. The VCU results, while reflecting both yield potential and disease resistance of a variety, fail thus to represent the situations in farm fields, where the farmer would use chemical plant protection when there was a risk of significant crop failure. The plots were fertilized by a basal application. Before 2000 the fertilization was done before sowing by placement across the rows, along the replicates. After 2000 the fertilization was gradually changed to row placement in sowing. The use of fertilizers depended on cropping history, soil type and fertility and was comparable to standard practices in Finland. The typical nitrogen (N) level was 60 kg N $ha^{-1}$ on organic soils and 80−100 kg N $ha^{-1}$ on mineral soils. Since 2016, the maximum rate of fertilizer-N for oats and barley was set in accordance with the minimum requirements of environmental compensation in 2015–2020 (Finnish Food Authority, ruokavirasto.fi). The rate has been 100 kg N $ha^{-1}$, when the percentage of the soil organic matter (SOM) is lower than 6 %. At SOM 6–12 % the maximum rate has been 90 kg N $ha^{-1}$, at 12–20 % SOM it has been 80 kg N $ha^{-1}$ and at 20–40 % SOM 60 kg N $ha^{-1}$ for a reference yield of 4000 kg $ha^{-1}$. For each increase of 500 kg $ha^{-1}$ in the reference yield, an extra 10 kg N $ha^{-1}$ has been allowed. The phosphorus (P) fertilization rates have been decreasing during the last few decades due to environmental protection goals. During the last 20 years, the median rate of P-fertilization in the VCU has been 12 kg $ha^{-1}$, with an interquartile range (IQR) of 8−15 kg P $ha^{-1}$. Before this the median rate was 35 kg P $ha^{-1}$, with an IQR of 25−43 kg P $ha^{-1}$. The median rate of potassium (K) fertilization has been 32 kg K $ha^{-1}$ (IQR 20−44 kg K $ha^{-1}$) in the last 20 years and 62 kg K $ha^{-1}$ (IQR 42−67 kg K $ha^{-1}$) before that.

Yields were harvested with a combine-harvester and weighed (kg $ha^{-1}$) after removing straw, weed seeds and other particles. The moisture content of the yield was determined by weighing grain samples before and after drying in the oven, or more recently by using grain moisture analyzers Dickey-john (DICKEY-john, 5200 Dickey John Road, Auburn, IL 62615 USA), Foss Infratec (FOSS, Nils Foss Allé 1, DK-3400 Hilleroed, Denmark) or Pfeuffer Granomat (PFEUFFER GMBH, Flugplatzstraße 70, 97318 Kitzingen, Germany). Yield was adjusted to 150 g moisture $kg^{-1}$.

The data were recorded as mean of three or four replicates. The data included 13 486 and 22 583 records of oats and barley, respectively. During the whole testing period of 1970–2018, 602 oat and 965 barley cultivars and advanced breeding lines (hereon together referred to as cultivars) were tested. Average growing time of cultivars was 99.6 days (range of 83–110 days) for oats and 93.0 days (range of 80–106 days) for barley. For the comparison of the responses of oats and barley to weather events, we selected from the original dataset varieties of both crops with approximately the same growing times. As in the VCU the spring cereals are usually sown at the same time at the same experimental site, this selection allowed us to match the development stages of interest of both crops with weather events. Thus, the cultivars with an average growing time between 90 and 100 days were selected. Consequently, the number of cultivars in the present analysis was 288 for oats and 686 for barley (48 % and 71 % of total number of cultivars, respectively) (Fig. 2).

The number of variety trials was 839 for oats and 1021 for barley. At some locations, more than one trial was conducted in the same year. In total, there were 576 and 606 different locations-by-year combinations in the data of oats and barley, respectively. In the cases, when there was only barley or oat trial in the combination, the data were not included in the analysis. Furthermore, when the weather data were not available or the sowing day was missing, the trials were omitted from the present study. Thus, the number of locations-by-year combinations used in this study was 341. The experiments used in this study were located at 14 sites stretching from southernmost Finland (Inkoo, 60°02′ N) up to latitude 64°39′N (Ruukki) (Table 1). The average number of cultivars per trials included here was 16.1 for oats and 22.1 for barley.

### 2.2. Farm yield data

The statistical services of Luke (https://stat.luke.fi/en/) regularly survey the annual yields of the main crops in Finland. The survey includes more than 3500 commercial farms chosen from a total of about 48 000 farms in Finland to give a comprehensive and reliable presentation of the practical farming. The crop yield data are published annually at the PXWeb-database of official statistics for the 16 ELY-centres (Centres for Economic Development, Transport and the Environment) of Finland (https://stat.luke.fi/en/). This database was used to estimate differences between the yields of oats and barley on farmers'

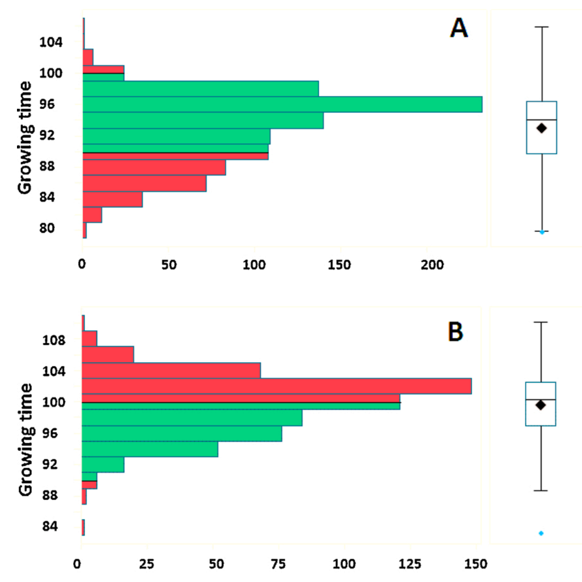


**Fig. 2.** The distribution of the growing times of barley (A) and oats (B) in the variety trials from 1970 to 2018, and the selected varieties (green bars). The distribution of growing times is presented as box-plots in right hand side, where the box encloses the middle half of the sample, with an end at the first and the third quartile. The Arithmetic mean is presented as a diamond inside the box. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

**Table 1**
The VCU testing sites in 1970 to 2018, with the number of test years and the period of testing.

| Site | Latitude N | Longitude E | Number of test years | Period of testing |
|---|---|---|---|---|
| Inkoo | 60° 02′ | 24° 00′ | 5 | 2003–2007 |
| Piikkiö | 60° 25′ | 22° 31′ | 7 | 2006–2012 |
| Mietoinen | 60° 37′ | 21° 55′ | 29 | 1970–2005 |
| Anjalankoski | 60° 45′ | 26° 49′ | 17 | 1970–1992 |
| Jokioinen | 60° 48′ | 23° 29′ | 27 | 1976–2018 |
| Kokemäki | 61° 15′ | 22° 20′ | 20 | 1970–1995 |
| Pälkäne | 61° 20′ | 24° 16′ | 30 | 1970–2005 |
| Mikkeli | 61° 41′ | 27° 16′ | 23 | 1984–2011 |
| Tohmajärvi | 62° 13′ | 30° 19′ | 20 | 1970–1995 |
| Laukaa | 62° 24′ | 25° 57′ | 32 | 1970–2007 |
| Ylistaro | 62° 56′ | 22° 31′ | 41 | 1970–2018 |
| Maaninka | 63° 09′ | 27° 18′ | 38 | 1976–2016 |
| Sotkamo | 64° 07′ | 28° 23′ | 12 | 2007–2014 |
| Ruukki | 64° 39′ | 25° 06′ | 40 | 1976–2016 |

fields (later referred to as farm data, FD) during the period from 1976 to 2018. Out of the 16 ELY-centres, 14 corresponded with the VCU testing sites and were included in this study. Management practice (fertilization, plant protection) data of farms are collected, but they are not public. However, 94 % of all field area in Finland is at present cultivated in accordance with the minimum requirements of the environmental compensation system (Yli-Viikari, 2019) and thus follow the same general lines as explained for the VCU data. The environmental subsidy system has been an important pillar of farm economy since 1995, when Finland joined the EU. Before this, the fertilization rates depended on the farm's economic state and management decisions, e.g. expectations of yield levels, weather conditions and willingness to take risks. It can be assumed that the fertilization levels used in the FD have deviated little from those in the VCU, especially during the last 25 years. The experiments in the VCU aim at achieving the full potential of the varieties, with deficiencies in nutrition out of question. The farmers have most probably followed similar guidelines in their quest for largest possible yields also before 1995, as then the grain prices were high enough to compensate for the inputs. Pesticide use, again, would have been and still is different in the FD than in the VCU. In the VCU, weed control and beginning from 2010 seed treatment have been allowed, but no other pesticides have been used, to reveal the disease resistance of the varieties. In the FD, decisions about pesticide use have been made by the farmers, depending on the severity of the pathogen/pest situation and expectations of the input/output ratio of the operations. The differences in the average yields between oats and barley were calculated for each ELY-centre-by-year combination, as explained for the VCU data.

### 2.3. Weather data

Based on the literature (Hakala et al., 2012; Peltonen-Sainio and Rajala, 2007; Peltonen-Sainio et al., 2011, 2015a, 2016, Trnka et al., 2011), the estimated time frames of agronomical events, crop growth phases and matching agrometeorological variables of interest for yield development were as follows: (1) delayed sowing (number of days after the average sowing dates in the beginning of May), (2) mean temperature during pre-heading phase (0–21 days before heading), post-heading phase (0–21 days after heading) and early growth (0–28 days after sowing), (3) accumulated precipitation during pre-heading phase (0–21 days before heading), post-heading phase (0–21 days after heading), and early growth (0–28 days after sowing), (4) precipitation during the whole growing season (from sowing to yellow ripening) and the whole growing season without first two weeks after sowing, (5) number of days with maximum temperatures exceeding 28 °C during a period of one week before and two weeks after heading (time frame of anthesis), and (6) duration of growing season (days from sowing to yellow ripening).

The weather data was provided by the Finnish Meteorological Institute (FMI) for each VCU site (Table 1). In some locations, like in Laukaa, the data from weather stations within a 20 km range was used. For the FD, one weather station was selected for the weather data within each ELY-centre.

### 2.4. Imputation of missing growth stage dates

In the VCU the plots of oats and barley were established on the same or on consecutive days. The dates of heading (Zadoks growth stage 55) (Zadoks et al., 1974) and yellow ripening (growth stage 92) depended on cultivar. The average dates of the growth stages were calculated by using certain oats and barley cultivars which had the average growing time between 90 and 100 days. The dates of heading and yellow ripening were not available for all trials. The proportion of missing dates was 0.61 for heading and 0.29 for yellow ripening. Photoperiod plays a key role in timing of phenological stages (Bleken and Skjelvåg, 1986). Thus, in a typical year, the duration of the period from sowing to maturity was shortest at the experimental sites with the longest photoperiods in the north. The phenological stages may thus have coincided with those in the more southern locations despite the later sowing dates. Missing dates were estimated accordingly by using the known days and latitudes. The following multiple linear regression model was separately fitted for heading and yellow ripening to estimate missing dates:

$$\text{date}_{ijk} = \mu + \text{species}_i + \text{year}_j + \beta_1\,\text{lat} + \text{year}_j \times \beta_2\,\text{lat} + \varepsilon_{ijk}$$

where $\text{date}_{ijk}$ is the known date for kth trials, $\mu$ is the intercept, $\text{species}_i$ is the effect of ith species (i = barley, oats), yearj is the effect of jth year (j = 1970,. . ., 2018), $\beta_1$ is the regression slope for latitudes of the location. $\text{Year}_j \times \beta_2\text{lat}$ allows for regression slope to vary from year to year (i.e. in some years heading or yellow ripening occurs simultaneously in the whole study area, in some years differences can be more than 3 weeks). Finally, $\varepsilon_{ijk}$ is the residual error.

All the effects in the modelling of sowing date were significant ($p < 0.001$). $R^2$ was 0.51. Year and latitude-by-year interaction effects were the most important predictors. The average difference in sowing dates between latitudes 61 °N and 64 °N was -2.2 days (south earlier), but this difference varied widely between years: from -11 to 4 days (i.e. in some years south was 11 days earlier than the north, in some years sowing was dated 4 days earlier in north than in south). Longitude played a clear role: the difference between 22 °E and 28 °E was 2.8 days (west earlier) and variation between years ranged from 0 to 5 days. When modelling heading date, all the effects were significant ($p < 0.001$) except year-by-longitude. The heading dates were available only from the year 1976 onwards, and therefore the years before 1976 were excluded from later analysis. $R^2$ was 0.67. Year and latitude-by-year interaction effects were the most important predictors. The average difference between 61 °N and 64 °N was -3.3 days (south earlier) and the difference varied widely between years: from -15 to 11 days. Differences in longitudes were smaller: the average difference between 22 °E and 28 °E was 2.4 days (west earlier) and statistically significant variation between years was not found. When modelling ripening date, all the effects were significant ($p < 0.001$), except year-by-longitude. $R^2$ was 0.67. Year and latitude-by-year interaction effects were the most important predictors. The average difference between 61 °N and 64 °N was -9.7 days (south earlier), but this difference ranged from -19 to 1 days depending of year. Longitudes played a small role in the model: the average difference between 22 °E and 28 °E was 0.8 days (west earlier) and statistically significant variation between years was not found. The residuals of the three models showed that the difference between the true and the estimated date of sowing, heading or ripening was typically less than 7 days.

### 2.5. Statistical methods

The yield data from each trial were analyzed separately and, for each cultivar, the mean dry matter yield was determined by the staff of the respective experimental location. In this study, these means were used as the basic recordings. The validity of the data was checked and only a few very low yields were detected and were estimated to have little influence on the results. Other possible outliers were not omitted from the analyzed data.

The mutually comparable yields for comparing the two crops were calculated for each trial by using a model that treated cultivar and trial as independent variables. Both crops were analyzed separately. Then the yield difference (oats minus barley) was calculated for each location-by-year combination. Next the difference was modelled using a single weather variable as independent variable in the analysis of variance. Most weather variables were categorized into three levels with equal number of trials, because the relationship between the weather and the difference in yield was not linear. Only in a few cases a continuous variable was used: number of days with maximum temperature exceeding 28 °C and the effects of the delayed sowing (in days). The study was divided into periods (1976−1986, 1987−1996, 1997−2006, 2007−2018), which were used in the model, because plant breeding has increased the difference in yield potential between oats and barley clearly during the whole study period (Peltonen-Sainio et al., 2015b; Öfversten et al., 2004). The possible bias caused by simultaneous changes in breeding and climate could in this way be eliminated from the results.

Similar modelling procedures were performed for the FD.

## 3. Results

### 3.1. Average yield differences of oats and barley and effects of breeding

At the beginning of the study (in 1970), the yield potential of oats was higher than that of barley, but by 2018 this difference had reversed. The average annual increase in barley yield compared to that of oats was 8.3 kg ha$^{-1}$ per year (se = 2.3 kg ha$^{-1}$, $p < 0.01$). For the first two 10-year periods in this study (from 1976 to 1996), the yield of oats was about 300−370 kg ha$^{-1}$ higher than that of barley ($p < 0.01$) in the VCU (Table 2). After the turn of the century, during the period 2007–2018, the yield potential of barley was 376 kg ha$^{-1}$ higher than that of oats ($p <$ 0.01). When calculated over regions and years, the FD yields of both oats and barley were about 60 % of the yields in the VCU. The differences in the yields of the two species were smaller in the FD than in the VCU, and barley yields were significantly ($p < 0.01$) higher already in the period 1997–2006 (Table 2).

The median yields were very similar in both species, when only results of the VCU on the same sites were considered. The median yield of oats was 4798 kg ha$^{-1}$ (sd 1173; range was from 913 to 8118 kg ha$^{-1}$) and the median yield of barley was 4812 kg ha$^{-1}$ (sd 1282; range was from 622 to 8712 kg ha$^{-1}$) during the period 1970−2018. In the yields of each experiment site and year, 14 % of the differences were explained by the general weather conditions, 16 % by other systemic site differences and 70 % by other factors. The latter includes factors such as differences in local weather conditions, e.g. there are big differences in precipitation between eastern and western Finland during the same growing season.

**Table 2**
The shift of the average yield differences between oats and barley in the variety trials (VCU) and in the farm data (FD), oats minus barley in kg ha$^{-1}$. Significant ($p < 0.05$) yield differences only are shown.

| | VCU | | FD | |
|---|---|---|---|---|
| | Yield difference (oats-barley) kg ha$^{-1}$ | significance | Yield difference (oats-barley) kg ha$^{-1}$ | significance |
| 1976−1986 | 296 | $p < 0.001$ | – | ns |
| 1987−1996 | 366 | $p < 0.001$ | 57 | $p = 0.03$ |
| 1997−2006 | – | ns | −96 | $p < 0.001$ |
| 2007−2018 | 376 | $p < 0.01$ | −216 | $p < 0.001$ |

### 3.2. Cool early season promotes yields, but barley suffers from excess rain

Yields of both species were highest, when sowing was at the beginning of May (data not shown). Delay in sowing is usually due to delayed drying of the fields due to late snow melting or precipitation occurring during the desired sowing season. Delayed sowing may lead to too warm and dry conditions during early growth phases. With delayed sowing, barley yields decreased more than those of oats, which resulted in an average yield difference of 20 kg ha$^{-1}$ day$^{-1}$ of delay of sowing in favor of oats in the VCU data ($p = 0.03$) and 6 kg ha$^{-1}$ day$^{-1}$ in the FD ($p =$ 0.01).

In addition to the positive effects of early sowing, cool early season (1–28 days after sowing) temperatures increased yields of both crops (Fig. 3a). In the VCU, there were no significant differences in the yields of barley and oats in the low (7.8–11.3 °C) and high (12.9–17.2 °C) temperature categories, but in the medium temperature category (11.3–12.9 °C) the yield of barley decreased to a level 197 kg ha$^{-1}$ lower than oats ($p = 0.02$). In the FD, the barley yields were slightly (65−70 kg ha$^{-1}$) but significantly ($p < 0.01$) higher than oats yields in the low and medium temperature categories, but there was no difference in the yields in temperatures above 13° (Fig. 3a).

High precipitation during early growth decreased the yields of barley in the VCU and of both crops in the FD. The average yield of oats was 359 kg ha$^{-1}$ higher than that of barley ($p < 0.001$) at high precipitation in the VCU, while at lower precipitation levels there were no yield differences (Fig. 3b). In the FD, barley yields were significantly higher than those of oats at low and medium precipitation. While at high precipitation the yields of both crops decreased, barley yields decreased more than oats, resulting in similar yields of both species (Fig. 3b).

### 3.3. Cool temperatures at grain number determination favor oats

In Finland, the number of grains is primarily determined from 1 to 21 days before heading, at a stage of about 33–60 on the Zadoks growth scale (Peltonen-Sainio and Rajala, 2007; Zadoks et al., 1974). When this “yield window” period was cool (average daily temperatures of 11.1–14.8 °C), oat yields increased, while there was little change in barley yields. Consequently, oat yields were on average 186 kg ha$^{-1}$ higher than those of barley in the VCU ($p = 0.02$) at the coolest temperature category. There were no yield differences at higher temperatures (Fig. 3c). In the FD, the differences between oats and barley were smaller, but in favor of barley, with 60 kg ($p = 0.01$) and 69 kg ($p <$ 0.01) ha$^{-1}$ higher yields of barley in the lowest and highest temperature ranges, respectively (Fig. 3c). There were no significant differences in the yields of the two crops during this period by any of the precipitation conditions in the VCU (Fig. 3d). In the FD, low precipitation levels resulted in 114 kg ha$^{-1}$ ($p < 0.001$) and medium levels in 77 kg ha$^{-1}$ ($p$ $< 0.001$) higher yields of barley than oats, but in the wettest conditions there were no differences in yields of the two crops (Fig. 3d).

### 3.4. Cool temperatures and high precipitation at grain filling favor oats relative to barley

In the period from heading to three weeks after heading (i.e. anthesis and early grain filling), oat yields were 273 kg ha$^{-1}$ higher than those of barley at cool average temperatures in the VCU ($p < 0.01$), with no yield difference at warmer temperatures. In the FD, the yields of both species were the same in cool and medium temperatures, but barley yield was 112 kg ha$^{-1}$ higher than that of oats ($p < 0.001$) in the warmest temperature category (Fig. 3e). Very high temperatures (above 28 °C) during the time frame of anthesis (from one week before to two weeks after heading) decreased the yields of both crops in the VCU and yield of oats in FD (results not shown). Oats yields decreased more than those of barley. Each day of very high temperatures resulted in a 56 kg ha$^{-1}$

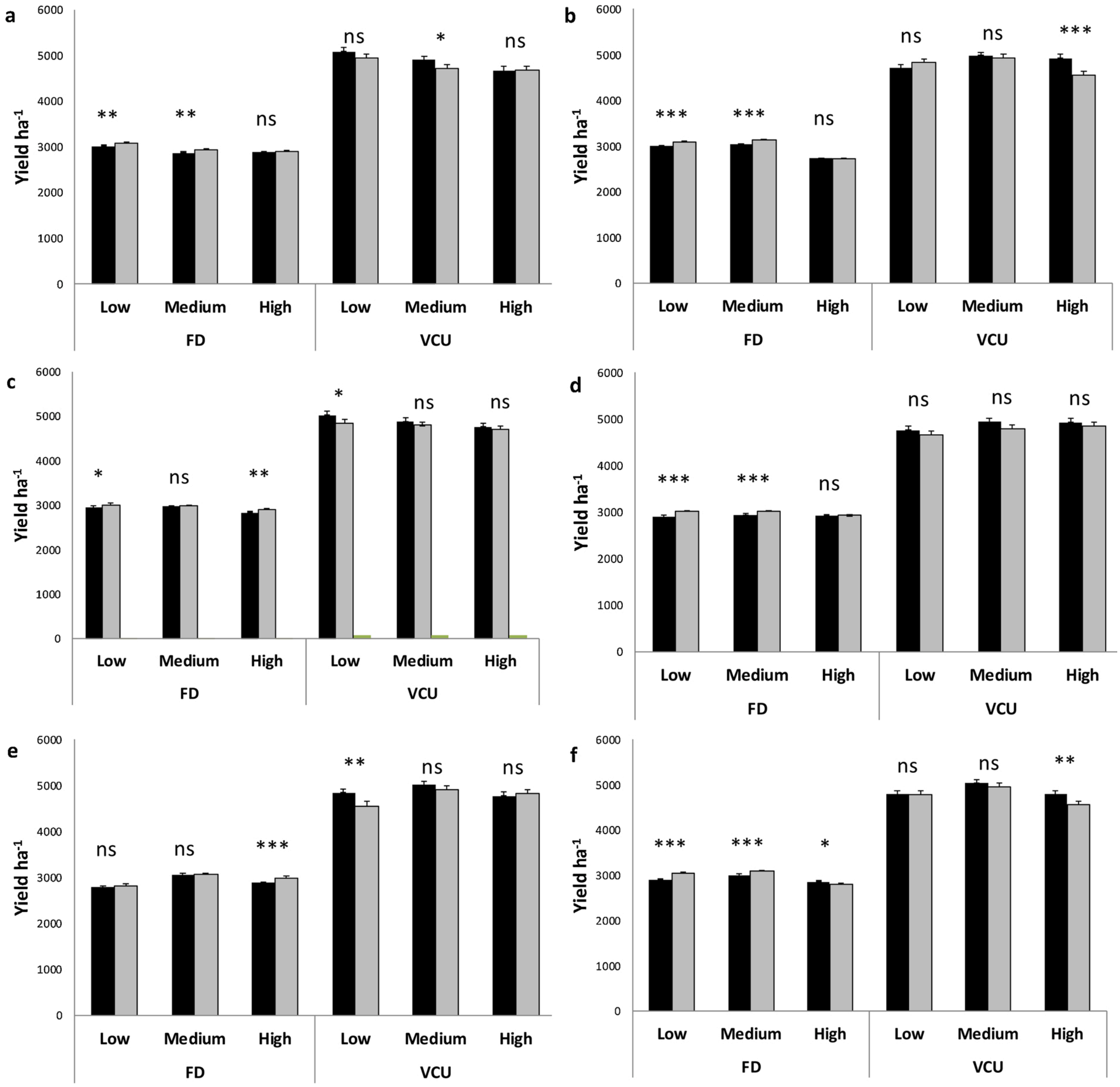


**Fig. 3.** The effects of average temperatures (a, c and e) and precipitation (rain sums, b, d and f) on the yields of oats (black columns) and barley (grey columns) in periods of: sowing to 28 days after sowing (a, b); 1 to 21 days before heading (c, d); and heading to three weeks after heading (e, f). The temperature and precipitation categories are in a) Low = 7.8-11.3 °C, Medium = 11.3-12.9 °C, High = 12.9-17.2 °C; b) Low = 0-32 mm, Medium = 32-52 mm, High = 52-128 mm, c) Low = 11.1-14.8 °C, Medium = 14.8-16.0 °C, High = 16.0-20.1 °C; d) Low = 0-27 mm, Medium = 27-49 mm, High = 49-164 mm, e) Low = 13.0-15.6 °C, Medium = 15.6-17.0 °C, High = 17.0-22.3 °C, and f) Low = 0-42 mm, Medium = 42-67 mm, High = 67-163 mm. *= significant at $p < 0.05$; **= significant at $p < 0.01$; ***= significant at $p < 0.001$; ns = not significant. Bars on the top of the columns denote the standard error of the yield difference. FD = the farm data, VCU = the variety trial data.

decrease in the yield of oats relative to barley in VCU ($p = 0.03$) and in a 37 kg $ha^{-1}$ decrease relative to barley in the FD ($p < 0.001$). Low and medium precipitation levels during this period resulted in similar yields of both species in the VCU (Fig. 3f). High precipitation, again, resulted in a significantly lower yield of barley (difference of 228 kg $ha^{-1}$, $p < 0.01$). In the FD, high precipitation resulted in slightly (47 kg $ha^{-1}$) but significantly ($p = 0.03$) lower yield of barley than of oats. At low and medium precipitation categories, barley yields were 140 kg $ha^{-1}$ ($p < 0.001$) (low) and 87 kg $ha^{-1}$ ($p < 0.001$) (medium) higher than oats (Fig. 3f).

### *3.5. Long growing time and high precipitation decrease barley yields more than oats*

The growth period of cereals is influenced by accumulation of $T_{sum}$. Cool growing seasons tend to lengthen and warm growing seasons shorten the growing period (Peltonen-Sainio et al., 2011). A longer growing period increases yields of cereals, except when the lengthening takes place at the final stages of development (Peltonen-Sainio et al., 2011). The yields of both oats and barley were highest in the medium length of growing season, as could be expected of crop varieties, which have been bred for the Finnish conditions (Fig. 4a). When the growing period lengthened from medium to long (from 90–95 to 95–117 days), the yield of barley decreased by 331 kg $ha^{-1}$ compared to that of oats in the VCU ($p < 0.001$). In the FD, the shortest growing time resulted in a 152 kg $ha^{-1}$ lower yield of oats than of barley ($p < 0.001$), but there was no difference in yields when the growing time was 90 days or longer (Fig. 4a).

Over the whole growing season, every 1 mm increase in precipitation per day increased oat yields relative to those of barley by 209 kg $ha^{-1}$ ($p < 0.01$) in the VCU. The difference was clearest in high precipitation, where the yields of both crops decreased, but barley yield decreased

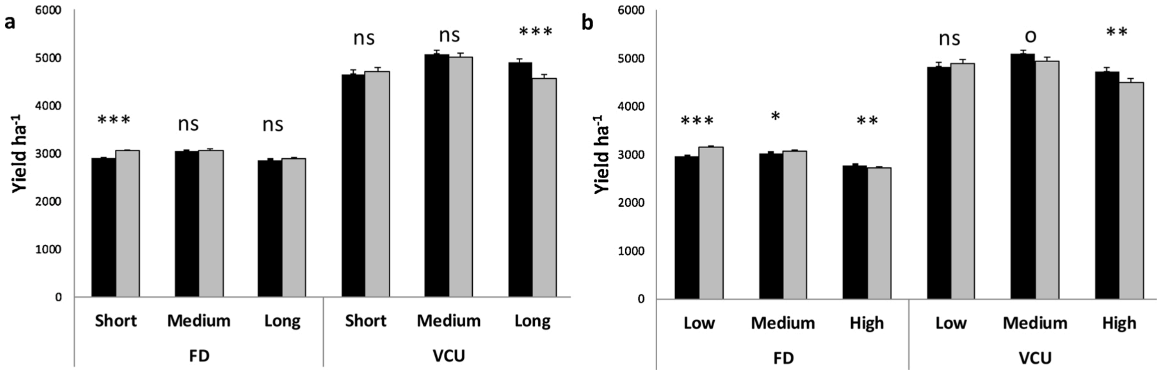


**Fig. 4.** The effects of a) length of growing period (days from sowing to maturity) and b) precipitation (mm day$^{-1}$ over the whole growing season) on yields of oats (black columns) and barley (grey columns). Categories in a): Short = 73-90 days, Medium = 90-95 days, Long = 95-117 days; and in b): Low = 0.6-1.8 mm, Medium = 1.8-2.4 mm, High = 2.4-4.1 mm day$^{-1}$. *= significant at $p < 0.05$; **= significant at $p < 0.01$; ***= significant at $p < 0.001$; O = trend ($p < 0.10$); ns = not significant. Bars on the top of the columns denote the standard error of the yield difference. FD = the farm data, VCU = the variety trial data.

more than oats, resulting in 216 kg ha$^{-1}$ yield difference in favor of oats ($p < 0.01$) (Fig. 4b). In the FD, the trend was generally the same with oat yields increasing relative to barley by 174 kg ha$^{-1}$ for every 1 mm increase in precipitation per day ($p < 0.001$). In low precipitation conditions, oat yield was 190 kg ha$^{-1}$ lower than barley ($p < 0.001$). In the high precipitation conditions, yields of both crops decreased just as in the VCU, again with barley yield decreasing more than oats, and thus the yield of oats was 55 kg ha$^{-1}$ higher than that of barley ($p < 0.01$). The result was similar, when precipitation during the very early growth stages (two weeks after sowing) was left out of calculations (data not shown).

## 4. Discussion

The general picture arising from the present study is that the yields of oats are either equal or significantly higher than those of barley in the studied weather events in the VCU data. This result was expected for the VCU data, where oat yields have been higher than those of barley until mid-1990's and barley yields significantly higher only since 2007 (Table 2). In the FD, barley yields have been significantly higher than those of oats from 1997 onwards. This conforms with the slightly, but significantly higher yields of barley in almost all climatic conditions. The only exceptions were the high precipitation at late development stage and when the average precipitation was high during the whole growing period.

### *4.1. The genetic potential of oats and barley in different weather events*

The present study shows no significant yield differences between oats and barley at low and medium levels of precipitation either in different growth phases or during the whole growing season in general. Even though no direct transpiration measurements were performed in the present study, our results give indirect evidence that oats and barley do not differ in their water requirements. Thus, our study fails to support the general understanding that oats would need more water than barley for the same yield (Chmielewski and Köhn, 1999; Peltonen, 1990a).

High precipitation had no effect on oats yields in early growth stages, but it decreased the yields of barley both during early growth and early grain filling. Moreover, the yields of both oats and barley decreased at high precipitation, when calculated over the entire growing season (Fig. 4b). This contradicts the earlier finding that increase in precipitation increases the yields of cereals, especially oats, at any growth stage before the maturation phase (Martin et al., 2001; Peltonen-Sainio et al., 2011). Barley was especially sensitive to excess moisture, contrary to reports of Mukula and Rantanen (1989a, 1989b). The sensitivity of barley to early growth flooding has been reported as a trait of barley where breeding has not brought relief yet (Hakala et al., 2012). With climate change, the number, duration and intensity of heavy rain events are expected to increase (IPCC et al., 2012). The reactions of both crops, but especially barley suggest an urgent need for improvement in their flood tolerance by breeding. As barley seems to be more sensitive to flooding, oats will probably cope better than barley in the more variable conditions in the future, unless radical improvements in the flood tolerance of barley appear in the cultivar market.

The yields of both oats and barley have been found to strongly depend on the number of grains m$^{-2}$ rather than grain weight (Peltonen-Sainio et al., 2007; Rajala et al., 2011; Sadras and Slafer, 2012). Grain number m$^{-2}$ is affected by the number of grain-bearing heads (main shoot + tillers) and the number of seeds per head. A cool start of the growing period favors a longer period of vegetative growth, increasing the number of shoots and heads and resulting in a higher number of seeds per m$^2$ (Evans and Wardlaw, 1976; Kristensen et al., 2011). According to the Finnish research, indeed, cool early growth has increased the yields of barley (Hakala et al., 2012) and cereals in general (Peltonen-Sainio et al., 2011). Delay in sowing may shift the early vegetative growth to a period, when the temperatures are already high and water availability reduced. In the present study, each day of delay in sowing penalized barley yield more than that of oats in both the VCU data and the FD. This result may be explained by earlier sowing leading to a cooler start of season, although there may not always be a connection between the two. However, the benefits of the cool start of growing season were evident in the present study, where the yields of both crops were highest at low early season temperatures (Fig. 3a). Barley was especially sensitive to delayed sowing, and it was more sensitive than oats to slight increase in the early season temperatures (Fig. 3a), which may reduce the future production potential of barley in comparison with oats.

In central Europe, both the number of tillers m$^{-2}$ and the number of grains per spike or panicle are decisive factors in yield formation (Sadras and Slafer, 2012). In the Finnish long-day conditions, fast early growth and canopy closure restrict the number of lateral shoots, especially if the early season temperatures are high and therefore the development is accelerated (Peltonen-Sainio et al., 2011, 2015a). Due to this, yield is mostly determined by the number of seeds of the main shoot ears or panicles (Peltonen-Sainio, 1994; Peltonen-Sainio et al., 2007; Rajala et al., 2011). Stresses, such as low radiation levels, nutrient deficiency or drought, occurring at the phase of development where the number of grains is determined are especially damaging (Arisnabarreta and Miralles, 2008; Chmielewski and Köhn, 1999; Estrada-Campuzano et al., 2008; Finnan and Spink, 2017; Mahadevan et al., 2016; Peltonen-Sainio, 1991, 1994, Peltonen-Sainio et al., 2011, 2016, Rajala et al., 2011; Sadras and Slafer, 2012; Sadras et al., 2017).

In the present study, the three-week period before heading represents the period of seed number determination and thus is the most sensitive phase for formation of yield potential (Peltonen-Sainio and Rajala, 2007). Low temperatures in this growth phase had a positive effect on the yields of oats, but there were no significant effects or differences on the yields of the two crops in the other temperature categories or in any precipitation categories. When the temperatures were very high (above 28 °C) during the time frame of anthesis (one week before and two weeks after heading), the yields of both oats and barley decreased, probably due to permanent reduction in the number of flowers and seed caused by the high temperatures (Ferris et al., 1998; Ingvordsen et al., 2018). Oat yields decreased significantly more than barley at these temperatures in both the VCU and the FD data. The reason for this may be the smaller number of cultivars and thus lower response diversity of oats to extreme heat. Hakala et al. (2012) showed that within a selection of barley varieties, there was significant diversity in the responses to high temperatures. With the increasing number and length of extreme temperature events in sight in the future (IPCC et al., 2012), efforts in breeding for tolerance to heat waves in oats would also be beneficial.

Due to insufficient network of solar radiation measurements near the VCU and FD testing sites in this study, we were not able to reliably study the effects of radiation on the yields of oats and barley. General information about the effects of lowered radiation on wheat has been gathered e.g. in an extensive European study of the sensitivity of different wheat varieties to extreme climatic conditions (Mäkinen et al., 2018). In this study, lowered radiation levels resulted in yield losses in most countries. However, in the northernmost parts of Europe the long day conditions during the growing season seemed to compensate for the lower incident radiation levels (Mäkinen et al., 2018). In Finland the day is longest at midsummer (24 June), around the crucial (pre-heading) period for yield determination in spring cereals (Peltonen-Sainio and Rajala, 2007; Peltonen-Sainio et al., 2011, 2015a, 2016). During this time the length of the day is 21.5 h in the northernmost site in the present study (Ruukki, 64.67 °N) and 19 h in the southernmost site (Inkoo, 60.04 °N) (see http://www.moisio.fi/taivas/aurinko.php). The heading of barley and oats takes place during the first two weeks of July (typically 10–12 July), when the day length is still 20.5 h in in Ruukki and 18 h in Inkoo. It is possible that even if the radiation intensities had been temporarily lowered, the long day length would have compensated for the transient reductions in radiation intensity, as suggested by Mäkinen et al. (2018).

In previous studies, elevated temperatures at grain filling have been found to decrease the yields of cereals by 80−140 kg $ha^{-1}$ $°C^{-1}$ increase in temperature (Peltonen-Sainio et al., 2016). Increase in temperatures usually accelerates the development of cereals and shortens different development stages, which tends to decrease both the seed number and the seed size (Hakala et al., 2012; Peltonen, 1990a, 1990b, Peltonen-Sainio, 1994; Peltonen-Sainio et al., 2011). In the present study, elevated temperatures at early grain filling resulted in similar yields of the two crops. Elevated temperatures are most harmful for crops with rapid development and short growing season (Peltonen-Sainio et al., 2011). This should have resulted in lower yields of barley compared to oats, as oats usually need higher $T_{sum}$ for maturation (Peltonen-Sainio and Jauhiainen, 2014). In the present study, however, oats and barley varieties of about the same growing time were chosen for comparison (Fig. 2). For barley the choice favored longer than average growing time and for oats shorter than average growing time, which resulted in about the same effects of higher temperatures during early grain filling.

Even though a longer growing period usually results in higher yield (Hakala et al., 2012; Peltonen, 1990a, 1990b, Peltonen-Sainio, 1994; Peltonen-Sainio et al., 2011), in the present study a very long growing time decreased yields of both oats and barley (Fig. 4a). Barley yields decreased most, and they were significantly lower than those of oats. A very long growing period indicates low average temperatures, which again are often associated with high precipitation. In accordance with this, higher than average precipitation during the growing period resulted in yield losses in both species, the response being more evident in barley than in oats. The difference between the crops was higher in the VCU data, but significant also in the FD (Fig. 4b). The larger decrease in barley yields corroborates our findings about the sensitivity of barley to excess moisture. However, delay in harvest as well as unfavorable maturing and harvesting conditions could also play a role in the decrease (Peltonen-Sainio et al., 2011). Moreover, cool season and high moisture levels may increase the occurrence of pathogens, the effects of which would show especially in the VCU data, where fungicides are not used.

To benefit from the potentially longer growing season in the future warmer climate, new varieties of crops with a longer growing time should be taken into cultivation (Peltonen-Sainio et al., 2009, 2015a). The growing period can extend in the spring and in the autumn. However, increases in precipitation in both winter and autumn may complicate the situation especially for barley (Ruosteenoja et al., 2016). In the spring, sowing might have to be delayed because of the higher winter rains that result in excess soil moisture, which increases the time needed for the soil to dry. In the autumn, light intensity decreases rapidly after the autumn equinox, and at the same time precipitation increases (Ruosteenoja et al., 2016). Because of the better tolerance of delayed sowing in the spring and flooding in general, extension of the growth period would improve the production potential of oats more than barley.

### *4.2. The farm yields of barley are mostly higher than those of oats in different weather events*

The weather events affected the FD and the VCU differently, so that barley yields were mostly higher in the FD and oat yields in the VCU data. The VCU data is based on comparisons of oats and barley in similar conditions and fields, with the aim to reveal differences in the genetic yield potential of the two crops. The FD data, again, are averages from the regional ELY centres, based on yield information from fields chosen by the farmer for cultivation of barley or oats. The superiority of barley in the FD may therefore reflect differences in cultivation practices. The common conception that oats are more modest than barley in regard to soil conditions, as also reported by e.g. Bebawi and Naylor (1978) and Mukula and Rantanen, (1989c), may have guided farmers to sow oats more often than barley in fields with less than optimal yield potential. E. g. the belief that oats will thrive also on acidic soils may have led to sowing oats more often than other cereals on turf fields, which are often situated around lakes and rivers, where flooding is common and may decrease yields (Mukula and Rantanen, 1989c).

However, a careful study of the allocation of crops on low, medium and high-quality fields in the years 2016 and 2017 showed no tendency of favoring oats on lower quality fields (Peltonen-Sainio and Jauhiainen, 2019). On the other hand, it has also been shown quite recently that farmers sow oats more often than other cereals on leased field, the properties of which are unknown to them (Peltonen-Sainio et al., 2018, data from 2011 to 2014). This indicates that farmers treat oats as a tough crop that would succeed reasonably well also in possible low-quality fields (Peltonen-Sainio et al., 2018). The present study covers 42 years from 1976 to 2018. During this period (in 1995) Finland joined the EU, after which many practices in farming have changed and there has been a significant decrease in the output/input ratio of the farm economy (Peltonen-Sainio et al., 2015b, https://stat.luke.fi/en/). While grain prices have plummeted to less than half of that before joining the EU, the prices of inputs, such as energy and fertilizers have doubled or even tripled, especially after the year 2000 (https://stat.luke.fi/en/). This has increased the importance of different subsidies in the farm economy, and farmers have had to accommodate their activities with the Common Agricultural Policy (CAP, https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/), and further with different environmental programs of the EU. From 2013 onwards, the CAP includes "greening", one part of which is diversification of crops (https://ec.europa.eu/info/food-farming-fisheries/key-policies/c ommon-agricultural-policy/income-support/greening_en). For the requirement of at least three crops in the rotation, the three spring cereals oats, barley and wheat are the best and easiest candidates in southern Finland. Moreover, an ecological focus area (EFA) of at least 5% of the total field area on farms more than 15 ha in southern Finland must be included for full CAP subsidy. This area must be a permanent conservation area, such as fallow or landscaping. Farmers are likely to place the EFA in their sub marginal soils, where they may earlier have sown oats. These changes may in part explain the recent finding that cereals are located evenly in fields (Peltonen-Sainio and Jauhiainen, 2019), unlike before, when farmers would choose fields of unknown or inferior quality for sowing of oats (Peltonen-Sainio et al., 2018).

According to Luke statistics in 2018 (https://stat.luke.fi/en/), the amount of plant protection chemicals used per cultivation area of barley was about 40 % higher than that of oats. This could mean three things: 1) oats are healthier than barley, 2) the smaller expectations for success of oats have led to smaller inputs in its cultivation or 3) both of these. The lower inputs in oats may have resulted in unrealized yield potential of oats compared to barley in climatic conditions where it would be superior, if given equal growth conditions as is the case in the VCU.

### *4.3. Role of plant diseases in the effects of weather events on oats and barley*

In the VCU data, barley yields were significantly lower than those of oats, when temperatures were low and precipitation levels high. In the FD, the yields of barley were slightly but significantly higher than those of oats except at the highest precipitation levels. The results point to the role of plant diseases as well as the use of plant protection methods affecting the yield of barley. High humidity promotes outbreaks of straw-borne diseases, which have an important role in Finnish cereal production (Jalli et al., 2011). Barley is known to be susceptible to an array of plant diseases, like leaf blotch diseases and mildew (*Blumeria graminis* f. sp. *hordei*), while oats have fewer plant diseases affecting yield in Finland (Jalli et al., 2011). In the VCU data, the difference is evident, as there are no fungicide treatments used against plant pathogens, in order to observe the level of disease resistance of the cultivars. Instead, farmers can use chemical plant protection when there is risk of significant crop failure. This, in addition to possible differences in the choice of the field may result in the differences of the yield balances between oats and barley in the VCU data and FD in the present study. According to recent research in Finland, management practices such as grading of seed, tailored crop rotations and use of fungicides may improve barley yields in average by 10–12% (Katja Kauppi et al., in preparation). In the future, the demand for reduced environmental load from agriculture may result in lower amounts of chemical pesticides. This would increase the importance of crop rotation and seed preparation, and the importance of oats as food and fodder crop at the expense of barley.

## 5. Conclusions

The genetic potential, as determined in the VCU, of oats was either equal or superior to that of barley in each of the studied weather events. In contrast, in practical farming (FD) barley yields were higher than oats except when precipitation was very high. The reasons for higher barley yield in the FD can be due to lower field quality in oats cultivation and/or higher inputs in barley, such as higher level of plant protection. Both crops require cool early season temperatures and medium precipitation levels for optimal yield. There was no indication of oats requiring more water for yield formation than barley. Both crops suffered from excess rain, barley more than oats. Barley was more sensitive than oats to delayed sowing and to increased temperatures during early growth. During the time frame of anthesis, temperatures above 28 °C decreased the yields of oats more than those of barley. When the growing time was very long, barley yields were significantly lower than oats yields. This was possibly due to lower growing season temperatures associated with higher precipitation levels, which were shown to significantly decrease the yields of barley compared to oats. Low temperatures and high moisture levels also favor pathogens, for which barley is more susceptible than oats.

Climate change will challenge crop production in Finland and globally. Farmers' choices of locally suitable crops and their varieties will help them to adapt to climate change. In the light of the present findings, oats will adapt to the future climatic conditions better than barley, especially if winter-time moisture, early season temperatures and early and late season precipitation increase and if heavy rains become more frequent. Farmers should avoid the cultivation of either oats or barley in fields with difficulties in water percolation. For the yield potential of oats to realize itself in different climatic conditions, it should be cultivated in at least as good conditions as barley. Flood tolerance of barley should be improved, as well as tolerance of both crops but especially oats of very high (> 28 °C) temperatures.

## CRediT authorship contribution statement

**Kaija Hakala:** Writing - original draft, Writing - review & editing. **Lauri Jauhiainen:** Formal analysis, Writing - review & editing. **Ari A. Rajala:** Writing - review & editing. **Marja Jalli:** Writing - review & editing. **Marja Kujala:** Writing - review & editing. **Antti Laine:** Writing - review & editing, Project administration.

## Declaration of Competing Interest

The authors report no declarations of interest.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2020.107956.

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