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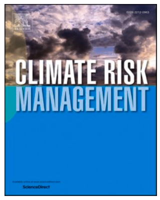

Climate change, precipitation shifts and early summer drought: An irrigation tipping point for Finnish farmers?

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ABSTRACT

In Finland early summer droughts are common. They cause yield losses (Y_{Loss}) of spring cereals, barley, oats and wheat, that cannot be compensated for later in the growing season. To support farmers in deciding whether to switch or not from rainfed to irrigated production, more data and understanding are needed on precipitation, its regional and interannual variation, caused Y_{Loss} and the cost-effectiveness of irrigation investments. This study aims to assess the spatiotemporal variation in early summer droughts and Y_{Loss} for spring cereals in the drought-prone Southwest Finland using past weather data (1971–2020). Furthermore, probability of early summer droughts was estimated based on two climate models, MPI-ESM and HadGEM2 and two greenhouse gas concentration scenarios, RCP4.5 and RCP8.5 for 2041–2070. Past data and future estimates of droughts were provided as 10×10 km^2 gridded data. A cost-benefit analysis was used retrospectively to estimate the feasibility of irrigation in 1991–2020. Two irrigation systems were found to be economically feasible for larger farm units and in the case of high farm yield levels. However, projected changes in future precipitation were not substantial for the critical yield determination phase of cereals. Hence, the change in precipitation *per se* does not necessarily encourage farmers to invest in irrigation in the future but further expanding farm size and higher future cereal yields might act as additional incentives. To conclude, this novel data on precipitation patterns, caused Y_{Loss}, and economic feasibility may promote irrigation as a key measure to reduce production uncertainties and yield variability in high-latitude conditions, although early summer droughts are not necessarily increasing.

1. Introduction

Global food production should be increased to meet the need of the growing population with higher standard of living, but with limited land and water resources. Agriculture accounts for about 70% of anthropogenic fresh water resource withdrawals (Molden et al. 2007). The consumptive water use for crops of blue (i.e., irrigation) water has increased due to the expansion of the overall agricultural and irrigated land area, but in the 2000 s advances in agricultural technology and adaptation of more water-efficient irrigation methods have recently reversed the trend, e.g., in India, China and USA (Zohaib and Choi, 2020). Complementing

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conventional irrigation methods with, e.g., water-harvesting, and nutrient management have substantial potential to further increase the effectiveness of water usage and water productivity (Hoff et al. 2010, Kropp et al. 2019).

Global fresh water reserves are scarce, and since 1950 s the global arid area has increased by 1.1% per decade (Wang et al. 2018). Without irrigation the global production of currently irrigated food and fibre crops would decline dramatically. For example, 43% of cereal is produced on irrigated land and without irrigation their yield would be halved meaning a 20% reduction in global total cereal production (Siebert and Döll 2010). Regional differences are, however, substantial. As cereal production is largely rainfed in northern Europe, losses would be negligible if current irrigation were abandoned. On the other hand, cereals may currently exhibit "hidden" yield loss (Y_{Loss}) even in the northernmost boreal zone of Europe (Peltonen-Sainio et al. 2011). This loss has not yet encouraged farmers to switch from rainfed to irrigated agriculture as potatoes have remained the only irrigated field crop in Finland (Peltonen-Sainio et al. 2016a). As Finland has vast available water reserves, the withdrawals-to-availability ratio would likely be low (Menzel and Matovelle 2010) though some peaks on water consumption may occur due to a short period for optimal timing of irrigation (Peltonen-Sainio et al. 2015a). However, interannual and within-season fluctuation in precipitation is high, thereby challenging farmer's decision making on whether to invest or not in irrigation: e.g., the length of the payback period may be hard to foresee, and not least as cereal farmers have outdated irrigation systems if any, and no up-to-date expertise (Peltonen-Sainio et al. 2015a).

Precipitation is anticipated to increase or decrease in Europe under climate scenarios depending on region, thermal season and future time period. Based on 26 global climate model simulations from the Coupled Models Intercomparison Project Phase 5 (CMIP5, Taylor et al. 2012) in southern Europe the long-term mean soil moisture is projected to decline dramatically throughout the year (Ruosteenoja et al. 2017). In western and central Europe, it is projected to decline in the summer and autumn, while in northern Europe a decline is projected for the spring only (Ruosteenoja et al. 2017). By the mid-century (2040–2069) and end of this century (2070–2099) the monthly mean of the near-surface soil moisture is anticipated to decline by 4–5% and 6–7%, respectively, in April-May in northern Europe according to the Representative Concentration Pathway RCP8.5 (Ruosteenoja et al. 2017). This together with the projected earlier onset of the thermal growing season (Ruosteenoja et al. 2019) is likely to enable earlier sowing in the future (Olesen et al. 2012), as a continuum of an ongoing change in sowing times that started a couple of decades ago (Kaukoranta and Hakala 2008, Peltonen-Sainio and Jauhiainen 2014). In addition to changes in the mean precipitation, extreme precipitation events are projected to become more common. In northern Europe the maximum 1-day precipitation is projected to increase by 20% in the winter season and by 10% in the summer season, while the consecutive dry days are anticipated to decrease by 10% in the winter and increase by 20% in the summer (Lehtonen et al. 2014).

In Finland early summer droughts are common and have caused 7–20% of Y_{Loss} for spring cereals as an average over a 30-year period with the highest Y_{Loss} in the south-western coastal region (Peltonen-Sainio et al. 2011). Early summer drought occurs at the critical yield determination phase of spring cereals, i.e. the reproductive period when the yield potential is developed. This is associated with reduced grain set (Rajala et al., 2009, 2011). Reduced grain numbers for cereals cannot be largely compensated for by a higher grain weight (Peltonen-Sainio et al. 2007) or increased tillering and higher number of head-bearing stems, as tillering is in general suppressed by the long days of high-latitude conditions (Peltonen-Sainio et al. 2009). Thereby, early summer droughts cause irreversible declines in the cereal yield potential, even though the rains often become more common during the grain filling period (Peltonen-Sainio et al. 2016b). Furthermore, contrary to many other weather constraints, no response diversity to drought has been found among barley cultivars adapted to high-latitude conditions (Hakala et al. 2012). Because climate change may further increase the risk of water shortages in the early reproductive phase for cereals, it may be time to specify a possible tipping point for Finnish farmers to switch from high-latitude rainfed crop production to irrigation (Peltonen-Sainio et al. 2016a). For example, in western Switzerland irrigation was found to be a novel and feasible adaptation measure to cope with decreasing summer precipitation in the future (Klein et al. 2014).

Finland has vast fresh-water reserves available for irrigation close to the agricultural land (Peltonen-Sainio et al. 2015b). Hanasaki et al. (2010) estimated that 9%, 24% and 43% for wheat, barley, and rice, respectively, of the total global virtual water exports were fed with blue (irrigated) water. Hence, countries with abundant water reserves should consider the means to alleviate the pressure of outsourcing environmental problems related to the use of scarce water resources of the arid regions (Sandström et al. 2018).

Projecting future changes in grain yields in the changing climate poses high uncertainties. Depending on the crop model, modest yield increases, declines or no change may be projected for the boreal regions when considering the joint impacts of changing temperature, precipitation, solar radiation, and atmospheric CO_2 concentration. This was true even in scenarios for which the daily mean precipitation has been set to increase by 10% (Tao et al., 2017, 2020). Because field crop production in Finland is rainfed, farmers cannot yet learn from pioneers. Therefore, this study provides retrospectively quantitative data for the first time on the frequency and impact of drought episodes, and Y_{Loss} were coupled with estimations of investment costs and their payback periods. To support farmers in their decision making as to whether to switch or not from rainfed to irrigated production system, comprehensive data and more understanding are needed on regional and interannual variation in precipitation and their impacts on crop development and growth, as well as the cost-effectiveness of irrigation investments. Hence, the aim of this study was 1) to retrospectively assess the probability of early summer drought occurring at the most critical period for cereal yield determination in the Southwest Finland, 2) to estimate the impacts of spatiotemporal variation in drought on the Y_{Loss} for spring barley, oats and wheat and 3) to support farmers in their decision on whether to invest or not in irrigation by estimating the costs of irrigation and comparing them to the Y_{Loss} depending on accumulated precipitation (Acc_{Pr}) during the critical developmental phase of cereals (between 10th June and 9th July). This study area is the prime cereal production region in Finland and uses 57% of the total agricultural land (293,000 ha, 5,000 farms) for spring cereals and has the highest risk of Y_{Loss} caused by drought. Future precipitation projections for 2041–2070 (two climate models, HadGEM2-ES and MPI-ESM-LR, with two greenhouse gas concentration scenarios, RCP4.5 and RCP8.5) were used to assess whether the drought risk might substantially change in the future, but without assessing the impacts of changes on Y_{Loss} on profitability of irrigation.

2. Materials and methods

2.1. Observed temperature and precipitation in 1971–2020

The daily temperature and precipitation data for Southwest Finland for 1971–2020 was extracted from the 10 × 10 km^2 gridded data of the Finnish Meteorological Institute (Aalto et al. 2016). Fig. 1 depicts the selected research area and its grid points. In Southwest Finland, between 10th June and 9th July (i.e., when the critical yield determination phase takes place) in years 1971–2020, the average precipitation was 60 mm (with a standard deviation of 26 mm) and the average temperature was 15.3 °C (in years 1971–1995 15.0 °C and in years 1996–2020 15.6 °C).

2.2. Future temperature and precipitation scenarios

The estimates of the mid-21st century temperature and precipitation in Southwest Finland were based on Earth System Model (ESM) simulations from the CMIP5 (Taylor et al. 2012) utilized in the preparation of the Fifth Assessment Report of IPCC (2013). Uncertainties related to climate projections of the future are modelling uncertainties, uncertainty in future emissions and natural variation of climate. The uncertainties related to modelling uncertainties were estimated by investigating simulations made with several CMIP5 global climate models. Further, the uncertainties related to the uncertainties in future emissions were assessed by investigating CMIP5 ESM simulations forced by different future scenarios referred to as Representative Concentration Pathways (RCPs, Moss et al., 2010; van Vuuren et al. 2011). These RCPs have been named after each scenario's corresponding change in the radiative forcing caused by anthropogenic activity by the year 2100 relative to pre-industrial radiative forcing. Thus, the additional radiative

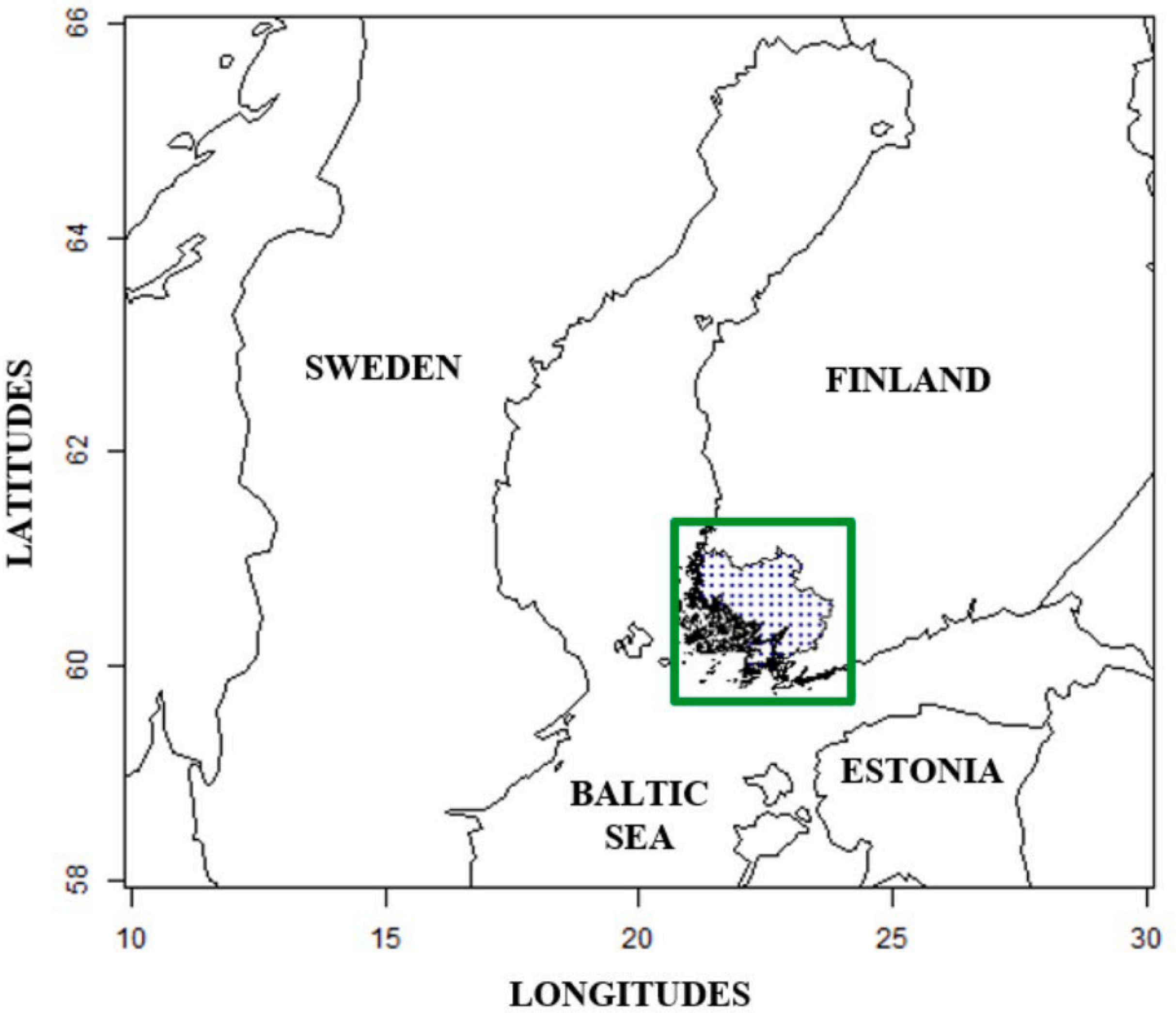

Fig. 1. Map and grid points of the study region in Southwest Finland.

forcing by 2100, was 4.5 Wm^{-2} in the midrange emissions scenario RCP4.5, and 8.5 Wm^{-2} in the high emissions scenario RCP8.5.

Based on 28 CMIP5 model simulations, the projected increase in Finland's mean temperature in June for the mid-21st century (2040–2069) relative to the 1981–2010, ranged under the RCP4.5 scenario approximately from 1 to 3 degrees, and under the RCP8.5 scenario from 1 to 4 degrees (Ruosteenoja et al. 2016). For Southwest Finland the multi-model mean increase of June mean temperature for the mid-21st century (2040–2069) relative to the 1981–2010 was 2.0 degrees under the RCP4.5 scenario and 2.6 degrees under the RCP8.5 scenario.

Further, the projected change in Finland's mean June precipitation for the mid-21st century (2040–2069) relative to the 1981–2010, based on 28 CMIP5 model simulations, ranged under the RCP4.5 scenario from −10 to + 22%, and under the RCP8.5 scenario from −11 to + 25% with a multi-model mean of an approximate 7% increase in both RCP4.5 and RCP8.5 scenarios (Ruosteenoja et al. 2016). In our study we selected CMIP5 ESM simulations downscaled by regional models in the European CORDEX initiative (Jacob et al. 2020), which were well able to simulate the present day seasonal cycle of precipitation in Finland and also represented well the above mentioned differences in the projected future mean June precipitation changes in Finland.

The performance of the downscaled model simulations was investigated by comparing the output of the historical simulations (here simulations for 1970–2005) to the statistics of the corresponding observed climate. These historical simulations were forced with

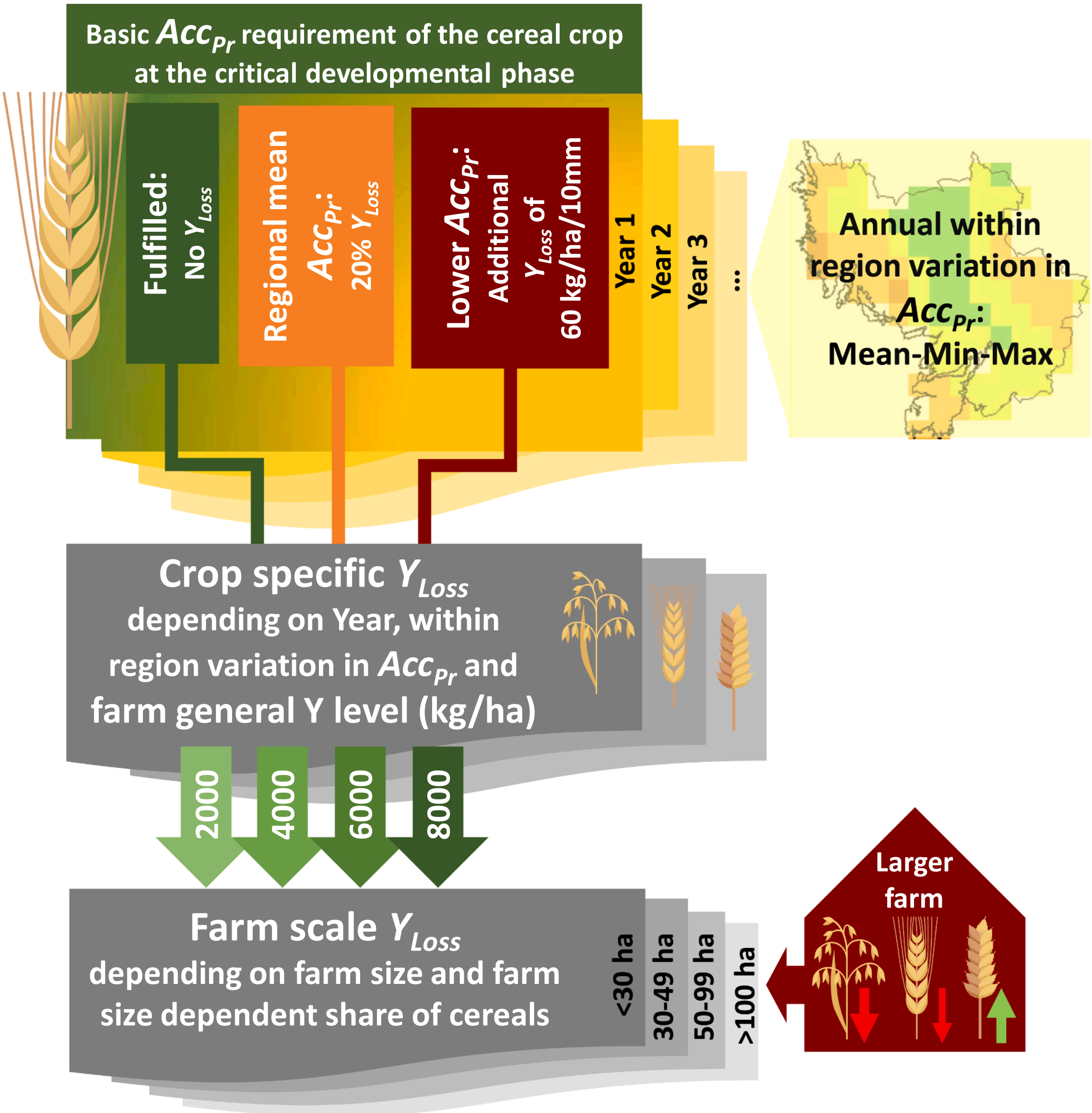

Fig. 2. Schematic presentation of the estimation process of yield losses (Y_{Loss}) on the basis of the regional mean, minimum and maximum precipitation (accumulated precipitation Acc_{Pr}, mm) at the yield determination phase, cereal species, farm general yield level (kg/ha), farm size (ha) and farm size dependent share (%) of land allocated to different cereal species.

historical records of climate forcing factors such as greenhouse gases, aerosols, and natural solar and volcanic changes. The seasonal cycle of the precipitation was checked by Data Evaluation for Climate Models (DECM) App (Gregow et al. 2019) developed for the Copernicus Climate Change Service C3S, and the bias was removed (Suppl. S1 and S2). From the model combinations good in capturing the seasonal cycle of the precipitation based on the ERA-Interim reanalysis (Dee et al. 2011) we selected two (Suppl. S3): the Max-Planck-Institute Earth System Model (Low Resolution, MPI-ESM-LR, hereon MPI-ESM) (Giorgetta et al. 2013) and the Hadley Centre Global Environment Model version 2 (Earth System, HadGEM2-ES, hereon HadGEM2) (Caesar et al. 2013) both downscaled by a regional climate model, RCA4 (Samuelsson et al. 2011). Simulations by these two model combinations captured well the range of the future June precipitation changes estimated by 28 CMIP5 model simulations by Ruosteenoja et al. (2016). The MPI-ESM(RCA4) simulations projected a decrease of 5% in the mean June monthly total precipitation from the period 1970–2000 to the period 2041–2070 under both RCP4.5 and RCP8.5. The HadGEM2(RCA4) simulations projected an increase of 30% under the RCP4.5 (21% under the RCP8.5) in the mean June monthly total precipitation from the period 1970–2000 to the period 2041–2070.

Further, the daily precipitation simulated by the RCA4 regional climate model, originally in 0.11 degrees resolution, were bi-linearly interpolated to the same resolution as the observational precipitation data (10 × 10 km^2) and then bias corrected with the quantile–quantile mapping method (Suppl. S1).

2.3. Estimation of Y_{Loss}

Spring cereals, barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.) and wheat (*Triticum aestivum* L.) were used as the model crops in this study, as their production is rainfed, they are widely cultivated prime crops in Finland, and in the study region they are susceptible to high risks of Y_{Loss} caused by early summer droughts (Rajala et al., 2009, 2011; Peltonen-Sainio et al., 2011). Barley is the most sensitive as an early maturing crop with lowest capacity to compensate for the losses, while wheat and oats are slightly less sensitive mainly because they are later maturing spring cereals (Peltonen-Sainio et al. 2011, 2016c, Peltonen-Sainio and Jauhiainen 2014) and oats are typically allocated to distant field parcels having often cool and moist conditions (Mukula and Rantanen 1989; Peltonen-Sainio et al. 2018). The Y_{Loss} was estimated for the most critical time period of the yield determination for spring cereals, which lasts from 215 ℃d to 465 ℃d (5 ℃ as a base-temperature) from sowing (Peltonen-Sainio et al. 2011), i.e., from early tillering to booting stage (ZGS23-45, Zadoks et al. 1974). This takes place between 10th June and 9th July. Accumulated precipitation of 100 mm during the yield determination phase was identified as the threshold amount that did not cause any Y_{Loss} according to the earlier studies that were based on prediction model. This model was developed in MTT Agrifood Research Finland (thereafter Luke) for free of charge use of farmers, industries and other stakeholders. This threshold was identified based on twenty years' multi-location data from Official Variety Trials by acknowledging the impacts of weather, soil and nutrient conditions (Peltonen-Sainio et al. 2011) (Fig. 2). According to this prediction model and the long-term past weather data, the mean precipitation in the most drought-prone region caused ~ 20% Y_{Loss} for barley when averaged over 30 years. This Y_{Loss} was estimated to be less for later maturing wheat (~15%) and oats (~10%) due to their slightly better capacity for compensation (Peltonen-Sainio et al. 2011). However, in years when Acc_{Pr} during the yield determination phase exceeded the long-term mean precipitation in the region, the Y_{Loss} was ignored, also in the case that Acc_{Pr} was lower than the threshold value of 100 mm. Thereby only significant Y_{Loss} was considered in economic analyses. An additional reduction in precipitation, compared to the long-term mean, caused for all cereals ~ 60 kg/ha Y_{Loss} (ranging between 47 and 75 kg/ha depending on year) per each 10 mm reduction in precipitation (Peltonen-Sainio et al. 2011, 2016c). The additional Y_{Loss} was weighed according to the annual average yield in the region. By summing up the percentage based and additional Y_{Loss}, the cereal specific Y_{Loss} was calculated for each year using the regional mean, minimum and maximum precipitation data on a 10 × 10 km gridded area of Southwest Finland (Fig. 2). The farm scale total Y_{Loss} was estimated for four farm categories depending on the farm average yield level, i.e. 2,000 kg/ha, 4,000 kg/ha, 6,000 kg/ha and 8,000 kg/ha, and by acknowledging the farm size: <30 ha (small), 30–49 ha, 50–99 ha and ≥ 100 ha (very large). However, the shares of different cereals in land use are dependent on the farm size (Peltonen-Sainio and Jauhiainen 2019), i.e. smaller farms favour especially oats more than wheat. For example, in 1990 s the relative shares of barley were 43% and 46% in small and very large farms, while shares of oats were 38% and 13% and those of wheat 19% and 41%, respectively. In 2010 s the corresponding figures were 43% and 44% for barley, 31% and 16% for oats and 26% and 40% for wheat. The impact of farm size on the shares of spring cereals were taken account by weighting the cereal specific Y_{Loss} according to the decadal shares of land allocated to different cereals, when estimating the total Y_{Loss} on the farm scale (Fig. 2). Hence, also the slightly shifts of cultivation areas of each cereal over time (Peltonen-Sainio and Jauhiainen 2020) were considered. By this means the annual total Y_{Loss} (kg/farm) in the study region was estimated for each of the past years for the 1971–2020 period by acknowledging three amounts of precipitation (mean, minimum and maximum), three cereals species differing in their sensitivity to early summer drought, four farm yield levels, four farm sizes and the farm size dependent shares of land allocated to different spring cereal species.

2.4. Estimations of investment and usage costs compared to benefits

A cost-benefit analysis (CBA) is a widely used economic tool to support decision-making processes. It is a mandatory analysis for every major regulatory initiative in USA and Canada (Bateman et al., 2002) as well for all the major projects in Europe that are funded by European Regional Development Fund and the Cohesion Fund (Sartori et al., 2014). With CBA how one or more project alternatives meet the critical values of an analysis can be assessed and the different alternatives can be ranked. On the other hand, CBA can be considered as a framework for decision makers to rule out unsuitable projects and compare trade-offs of different alternatives. It enhances disciplined and transparent decision making.

The basic principle of CBA is to compare the expected value of benefits with cost items during the life cycle of a given project. If the estimated net social benefits of a project are positive, the project is recommended. The CBA framework with nine steps by Boardman (2015) was developed to provide a guideline on the preparation of comparisons. The framework specified the following steps: (1) specify the set of alternative projects, (2) decide whose benefits and costs to count (standing), (3) identify the impact categories, list them, and select measurement indicators, (4) predict the impacts quantitatively over the life of the project, (5) monetize all impacts, (6) discount benefits and costs to obtain present values (*PV*), (7) compute the net present value (*NPV*) of each alternative, (8) perform a sensitivity analysis, and (9) make a recommendation.

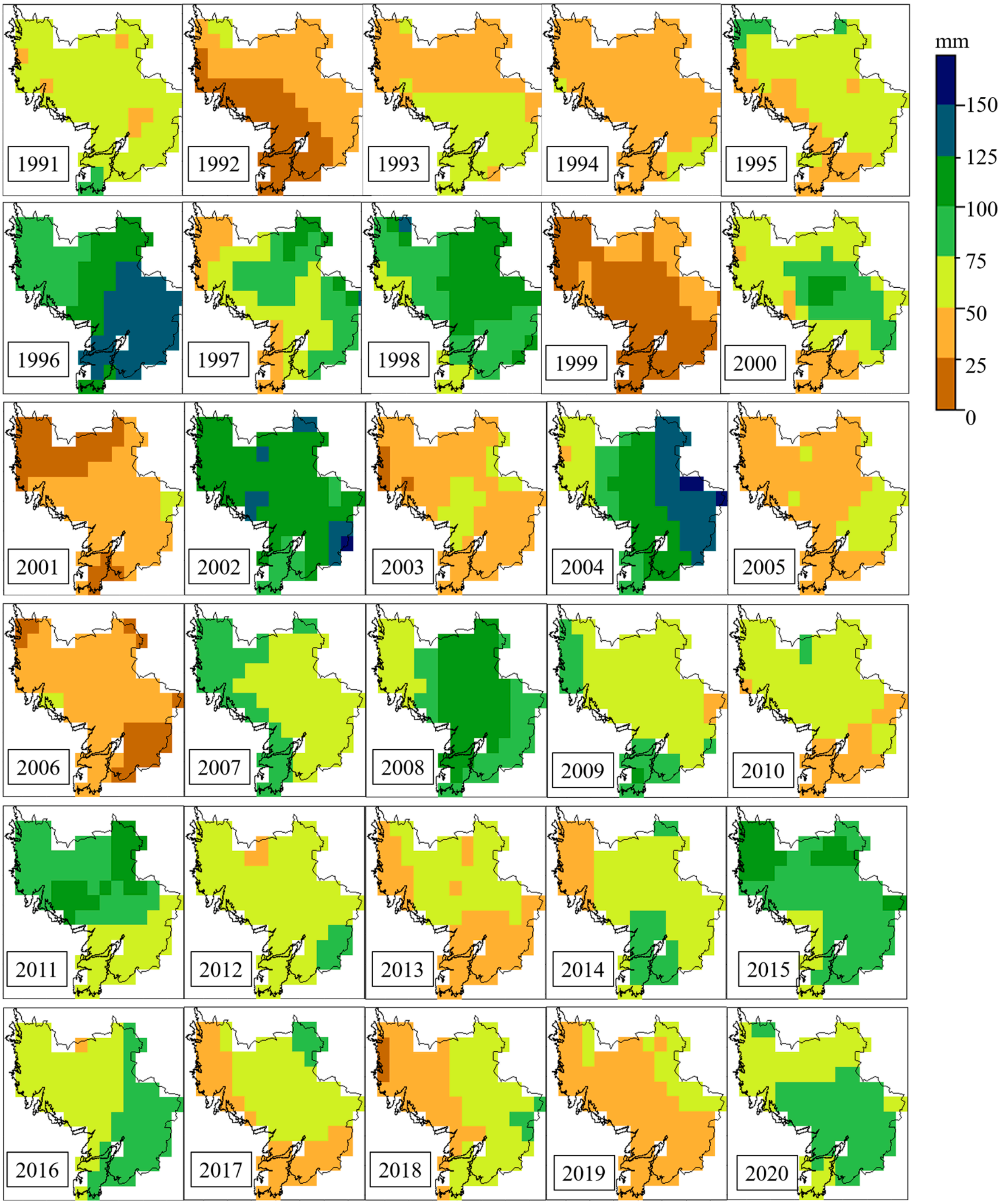

Fig. 3. Accumulated precipitation (mm) for the years of the recent past 1991–2020 in the study region of Southwest Finland during the yield determination phase of spring cereals.

The CBA approach was used to retrospectively (1991–2020) assess, whether it would have been cost-effective for Finnish farmers to invest in irrigation systems based on realized early summer droughts and Y_{Loss}. Due to high uncertainties, especially lack of long-term projections on changes in prices and costs, cost-effectiveness of irrigation was not analysed for future climates. In this study, the economic performance of three different irrigation methods were compared: self-propelled irrigation system, stationary irrigation system and subsurface irrigation system. (1) Although we considered other irrigation methods such as surface flooding, furrow method and drip irrigation, no data on costs were available from Finnish agricultural retailers and furthermore, they were not necessarily applicable methods for cereals and soils where they are grown. On the other hand, irrigation has not been implemented for cereals in Finland and hence, the farm-scale data on applicability and investment costs are minuscule. The pragmatic aim was for the first time to provide concrete and comprehensive information about the impacts of precipitation patterns on the cost-effectiveness of irrigation and thereby, consider potential of irrigation as an adaptation means for the farmers in the drought prone southwestern region of Finland. (2) The aim of the analysis was to provide support for the decision making. The cost-benefit analysis was conducted from the farmer's perspective and hence, it did not take into consideration what kind of externalities the irrigation might impose on the area, i.e., we did not consider how farm sizes and production capacity are spatially placed in the study region. The benefit items of the three irrigation systems were the expected avoided costs that the irrigation system would have provided during drought periods. The benefit items were compared to the costs which included the investment and operation expenses. Information on costs that each irrigation system would have caused for a farmer were compiled by contacting large number of national authorities and stakeholders (Suppl. S4). The

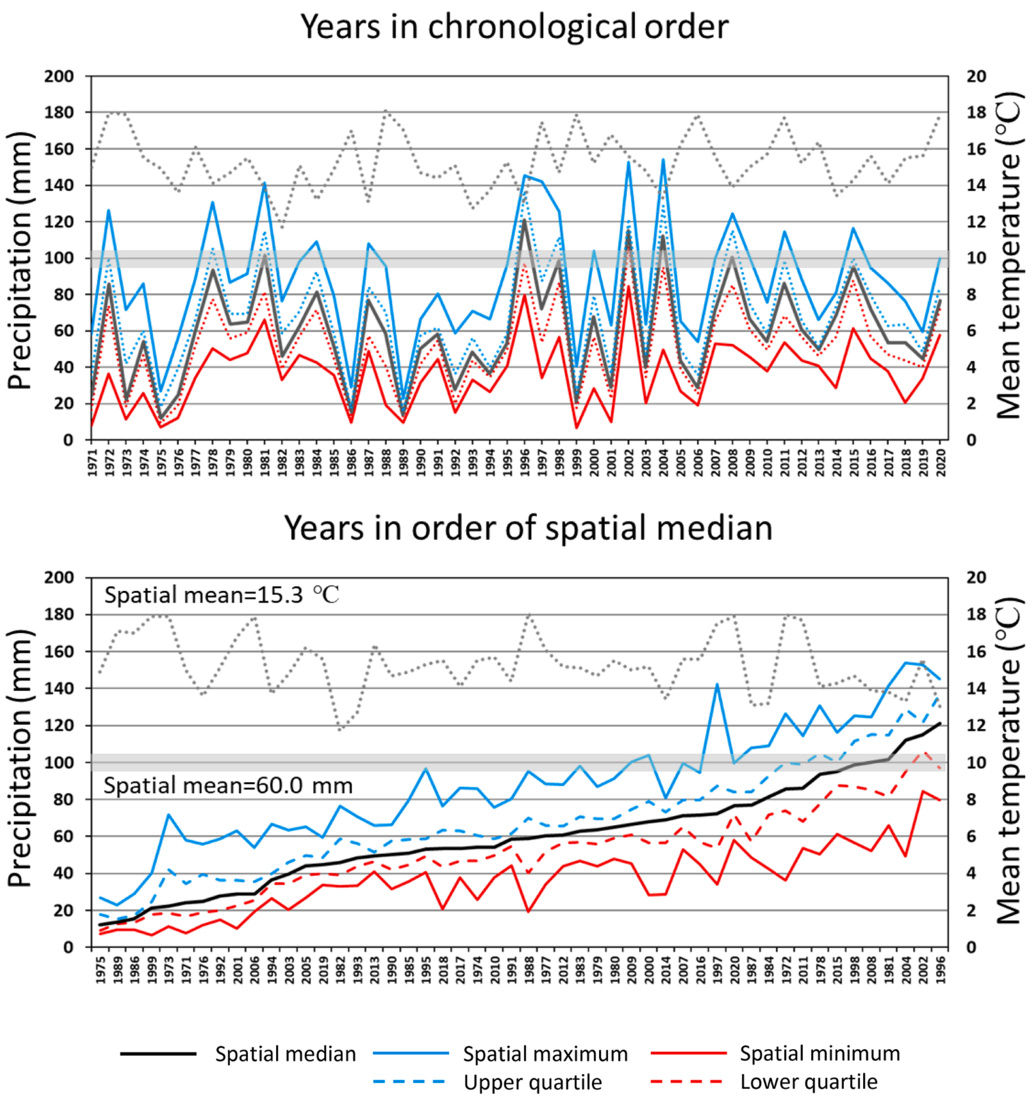

Fig. 4. Minimum, lower quartile, median, upper quartile, and maximum precipitation (mm) and mean temperature (°C, grey dashed line) during the critical yield determination period in the region of Southwest Finland for the last 50 years based on 10 × 10 km gridded data. The above panel is in chronological order and the bottom one is in order of the median precipitation. The grey horizontal line indicates the crop requirement of 100 mm precipitation.

costs and benefits were discounted for *PVs*, with 3% being the rate in calculations according to EU recommendations (Sartori et al., 2014). The net benefits of each irrigation system were then calculated by subtracting the *PVs* of the investment and administrative costs from the *PV* of avoided costs (Beecher, 1996) from the Y_{Loss} due to the irrigation system (6–7). Finally, a sensitivity analysis (8) was constructed from the *NPV* calculations and the results were analysed (9).

Minimum, mean, and maximum precipitation for the study region were used to estimate the yearly Y_{Loss} from 1991 to 2020 (n = 30) depending on the farm size (30, 50, 100, and 150 ha) and four farm scale yield levels (2,000, 4,000, 6,000, and 8,000 kg/ha). The *PV* (€) of the Y_{Loss} caused by droughts was then calculated with the equation [1], where the p is the weighted average cereal price, y is the Y_{Loss} caused by drought in kg and r is the discount rate (3%). The weight of each cereal was the proportion of each crop from their total area in the Southwest Finland in 2020 (Luke 2020). These weights were then used with 2020 market price data to calculate the averaged crop price (0.17€/kg). We assumed, that cereal price inflation is 0.7% (Official Statistics of Finland, 2021).

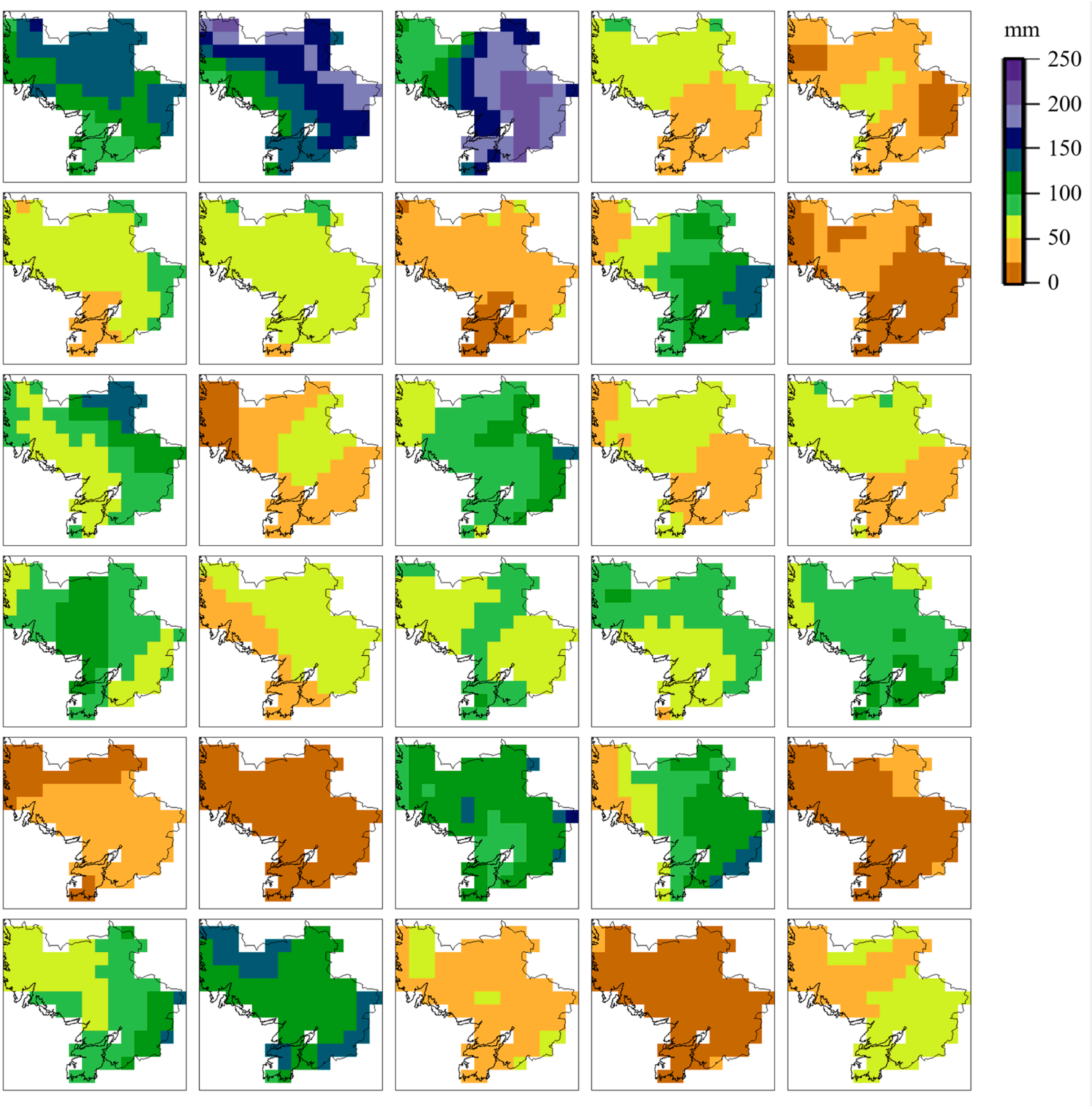

Fig. 5. Projected accumulated precipitation (mm) for the future period of 2041–2070 in the study region of Southwest Finland during the yield determination phase of spring cereals, according to the HadGEM2-ES climate model in the RCP4.5 climate scenario. These simulation data are not representing particular years but projections of single years during 2041–2070.

$$PV_{noirrigation} = \sum_{t=0}^{n} \frac{p_t y_t}{(1+r)^t} \tag{1}$$

The benefits of irrigation were derived by subtracting the *PV* of irrigation investment and operating expenses from the *PV* of Y_{Loss}. This yielded the *NPV* of each irrigation solution (equation [2]):

$$NPV_{irrigation=} \sum_{t=0}^{n} \frac{p_t y_t}{(1+r)^t} - \sum_{i=0}^{n} \frac{OE_t}{(1+r)^t} + \frac{I_t}{(1+r)^t} + (1-\varepsilon)^*(\frac{p_t y_t}{(1+r)^t}) \tag{2}$$

In this equation, the expected value of investments (*I*) and operational expenses (*OE*) for maintenance and labour are subtracted from the expected *PV* of drought damages to cereals. The last term represents the efficiency of the irrigation system where the coefficient ε can be used to simulate the efficiency of the irrigation system. We assumed full irrigation efficiency in the base scenario ($\varepsilon =$

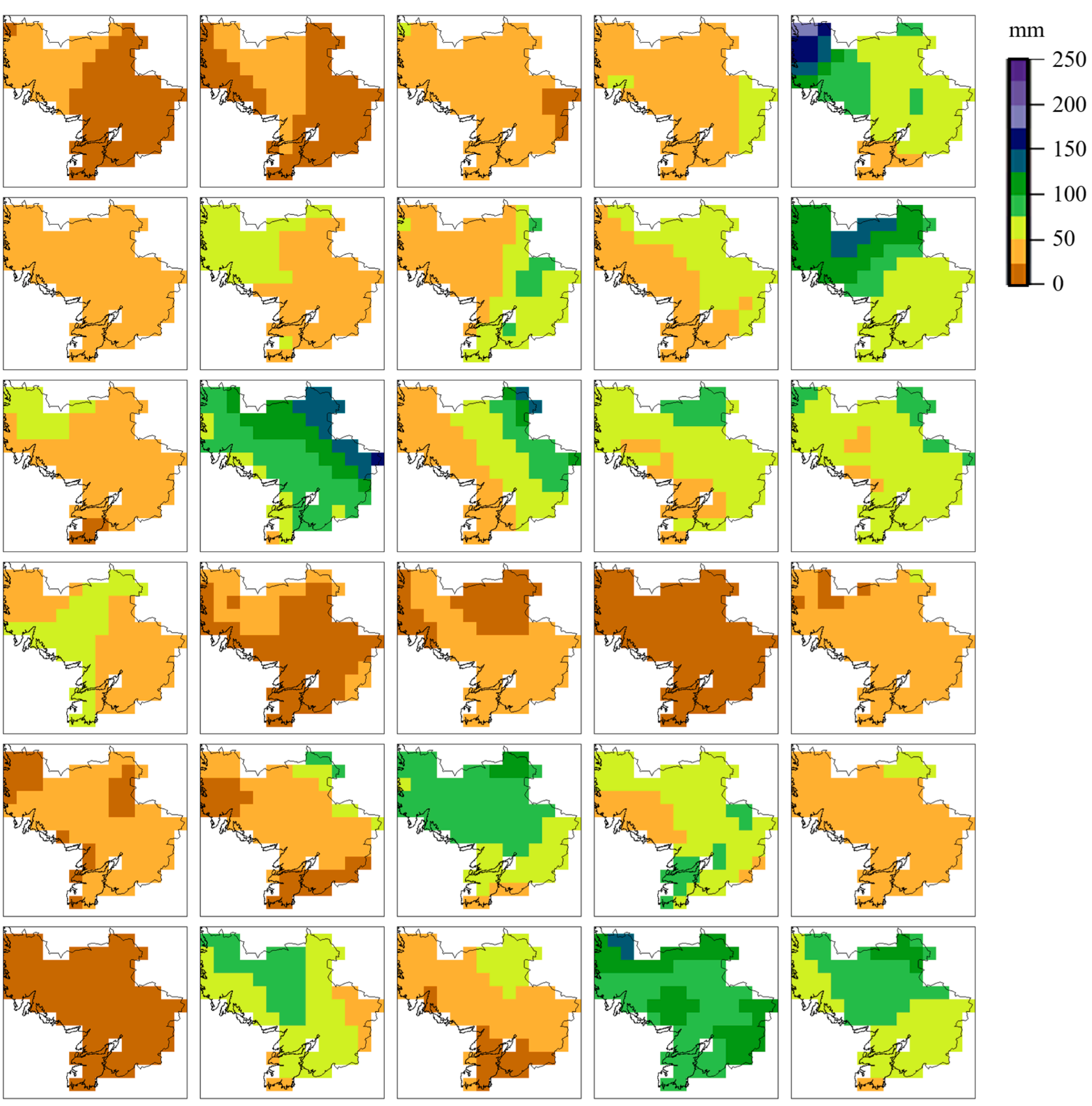

Fig. 6. Projected accumulated precipitation (mm) for the future period of 2041–2070 in the study region of Southwest Finland during the yield determination phase of spring cereals, according to the MPI-ESM-LR climate model in the RCP4.5 climate scenario. These simulation data are not representing particular years but projections of single years during 2041–2070.

1) and tested decreasing efficiency in the sensitivity analysis.

3. Results

3.1. Spatiotemporal variation in AccPr and Y_{Loss}

The Acc_{Pr} during the critical developmental phase of spring cereals varied considerably in the study region in Southwest Finland. For the long-term past period of 1971–2020 early summer droughts were very common (Fig. 3 and Suppl. S5). The median across the study region exceeded 100 mm of rain (i.e., the cereal requirement for attaining the regional yield potential) only four times in 50 years (Fig. 4). Due to high within region variation in the Acc_{Pr}, in 66% of the years the required precipitation of 100 mm was not reached in any of the 10 × 10 km grid area, while in 34% of years this was reached in at least one of the grids (Fig. 4). There was, however, a tendency of increased Acc_{Pr} till the 2000 s in decadal comparisons. Higher Acc_{Pr} correlated with a higher number of rainy days (Suppl. S6): when considering rains with > 5 mm precipitation, the last three decades had not only a higher mean Acc_{Pr} (52, 56, 61, 66 and 66 mm for 1970 s, 1980 s, 1990 s, 2000 s and 2010, respectively), but also a higher number of rainy days with > 5 mm precipitation (3.5, 3.6, 4.0, 4.5 and 4.7, respectively).

The two climate models were selected to represent differences in growing season projections for future precipitation patterns in Finland and the outcomes are shown in Figs. 5 and 6 (see also Suppl. S2 for the validation of the simulated precipitation data). The time period of critical yield determination phase was not fully identical for the past and the future Acc_{Pr} with about 10 days difference towards earlier calendar days in the future periods. This was to better match the future timing of the yield determination phase in

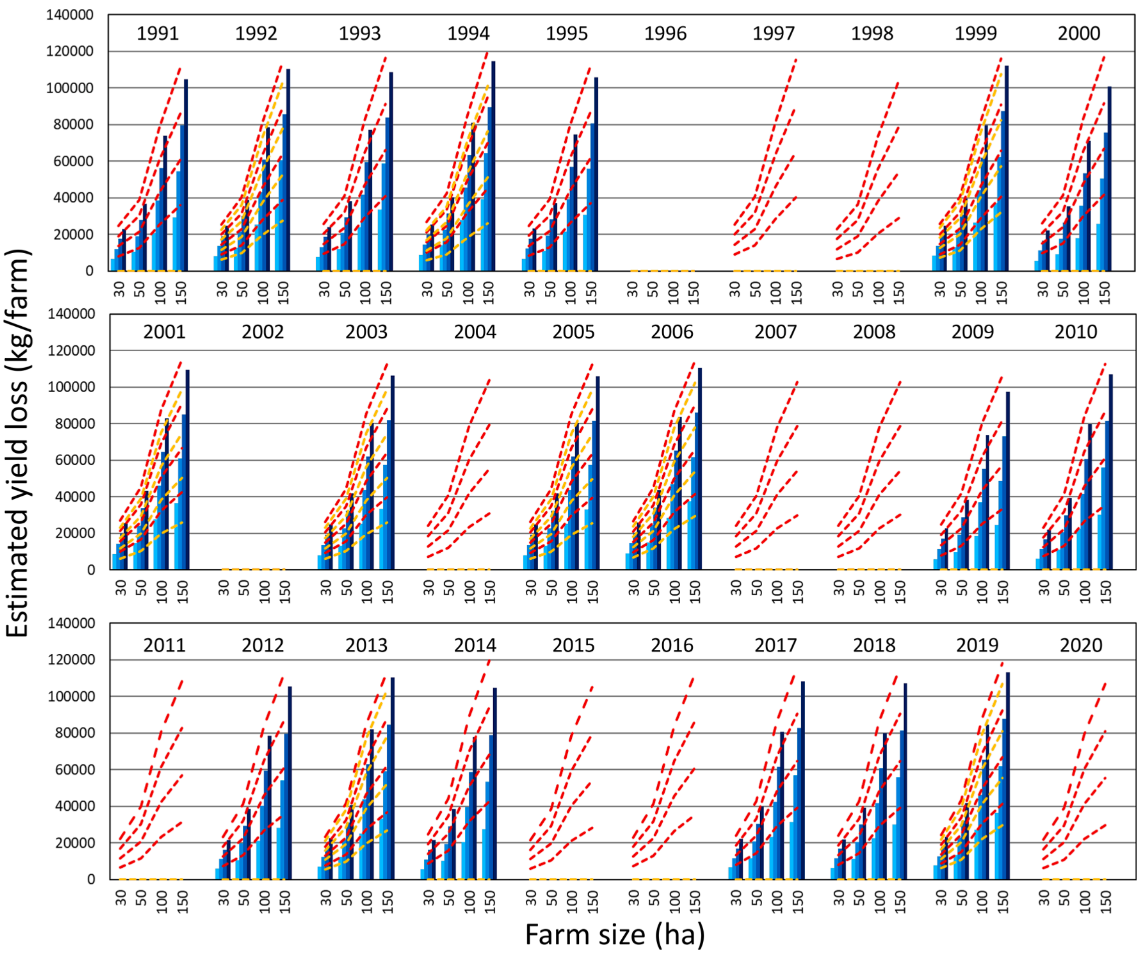

Fig. 7. The estimated average total farm-scale Y_{Loss} (kg/farm) depending on the accumulated precipitation (mm), farm size (ha) and farm yield level (kg/ha) in Southwest Finland for the years 1991–2020. The blue bars indicate the Y_{Loss} based on the mean precipitation: the lightest blue bar shows the Y_{Loss} at a farm yield level of 2,000 kg/ha followed by 4,000 kg/ha, 6,000 kg/ha and eventually 8,000 kg/ha shown with the darkest blue. The yellow dashed line shows the subregion with the highest precipitation and the red dashed line the subregion with the lowest precipitation during the critical growth phase in the study region (the uppermost yellow/red line is always for the very large farm and the lowermost for the small farm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cereals as sowing times are likely to be earlier in the future than today (Olesen et al. 2012). HadGEM2 projected a higher Acc_{Pr} for the yield determination phase than was the case according to the past data as the mean for the Acc_{Pr} across the 2041–2070 period was 70 mm for the RCP4.5 scenario and 66 mm for the RCP8.5 scenario (Suppl. S7 and S8), while the Acc_{Pr} was 60 mm for 1971–2020. Despite a higher projected Acc_{Pr} only 20% of the years reached the regional mean Acc_{Pr} of 100 mm according to the CRP4.5 emission scenario and 10% according to the CRP8.5 scenario. The MPI-ESM climate model projected early summer drought to become more severe in 2041–2070 than experienced during the past five decades, however, being close to that in 1970 s: the estimated mean Acc_{Pr} was 50 mm for both the CRP4.5 and CRP8.5 scenarios, and 100 mm of Acc_{Pr} occurred only once within the future 30 years period in the CRP4.5 scenario and two times in the CRP8.5 scenario simulations (Suppl. S9 and S10).

Regarding the past data, the 1970 s was the decade with the most frequent Y_{Loss} caused by insufficient early summer Acc_{Pr} (Suppl. S11), while both in the 2000 s and 2010 s four years without Y_{Loss} were estimated according to the mean Acc_{Pr} in the study region (Fig. 7). As is obvious, the total farm scale Y_{Loss} increased with increasing farm size. However, at least in half of the growing seasons in each decade some sub-regions did not suffer from any Y_{Loss}, i.e., in some parts of the Southwest Finland the crop requirement of 100 mm Acc_{Pr} during yield determination phase was achieved (Fig. 7 and Suppl. S11). This was especially the case in the 2010 s, when in eight out of ten years some parts of the region did not suffer from insufficient Acc_{Pr} (Fig. 3).

3.2. Cost-efficiency of investments on irrigation systems

When the *NPV* of the avoided costs of each irrigation system (Table 1) were calculated for each farm size and farm yield level combination, the monetary values were considered as the expected farm-scale savings from the system. A positive *NPV* means that the savings would exceed the investment and operation costs, while in the case of a negative *NPV* the avoided costs with the irrigation system would not be high enough to cover the investment and operation expenses.

In general, the net benefits for irrigation systems varied a lot depending on the farm characteristics. The stationary irrigation systems were found to be the most feasible and cost-efficient system. The estimated benefits exceeded the estimated investment and operation costs for most of the farm sizes in the case that the farm yield level was $\geq$ 6,000 kg/ha (Table 1). Self-propelled irrigation system was also cost-efficient, but the value of the expected avoided costs exceeded the investment and operation expenses only on the highest farm yield levels of 8,000 kg/ha and farm sizes $\geq$ 50 ha. The highest regional Acc_{Pr} values reduced Y_{Loss} compared to mean Acc_{Pr} and only stationary irrigation system had positive *NPV* provided that the farm-scale yields were 8,000 kg/ha. When Y_{Loss} was estimated with the lowest regional Acc_{Pr} values both self-propelled and stationary irrigation systems were cost-efficient in the case of larger farms and higher yield levels. The expected net benefits from subsurface irrigation did not exceed the expected investment and operation costs for any of the farm size and farm yield level combinations, even if acknowledging a government issued 40%investment subsidy, which was taken into account in the baseline scenario (Table 1). Nonetheless, subsurface irrigation was only valued based on its role as an irrigation system to mitigate drought induced Y_{Loss}. However, it provides dual benefits when used as a drainage system, which was not valued in these estimations.

4. Discussion

4.1. Past and future challenges brought by variability in precipitation typical for high-latitude conditions

Farmers are the ones who decide how and when to adapt agriculture to the changing climate (Sorvali et al. 2021). According to recent farmer survey in Finland, farmers need comprehensive and locally relevant information about current and potential future drought episodes, the Y_{Loss} they may cause, and the costs and benefits of the measures to cope with them (Peltonen-Sainio et al. 2021).

Table 1
Estimated net benefits (1,000 €/farm) of irrigation systems for the period of 1991–2020 depending on farm size (ha) and farm yield level (kg/ha). Positive net benefits are bolded and highlighted with green.

Irrigation system	Farm yield level (kg)	Estimated net benefits 1,000 €/farm)			
		30 ha	50 ha	100 ha	150 ha
Self-propelled irrigation	2,000	−58	−57	−99	−155
	4,000	−45	−36	−55	−95
	6,000	–32	−14	−12	−35
	8,000	−19	**8**	**32**	**25**
Stationary irrigation	2,000	−30	−31	−57	−93
	4,000	−17	−9	−14	–33
	6,000	−4	**13**	**30**	**27**
	8,000	**9**	**34**	**74**	**87**
Subsurface irrigation	2,000	−193	−321	−642	−970
	4,000	−180	−299	−598	−910
	6,000	−167	−277	−555	−851
	8,000	−154	−256	−511	−791

On the other hand, high variation in growing conditions is characteristic to high-latitude agriculture and one could argue that Finnish farmers are accustomed to coping with unpredictable weather conditions that cause crop failures, as well as high yields, but mostly something between the two. Hence, drought is a constraint among many others that cause Y_{Loss} (Peltonen-Sainio et al. 2016c) and this challenges farmers when trying to decide how and when to adapt (Peltonen-Sainio et al. 2020). In general, regionally relevant information about climate change is abundantly available (e.g., Ilmasto-opas 2020). However, science-based information is often blurred by middlemen, their attitudes, and opinions before it reaches a target group like farmers (Weber and Stern, 2011). Therefore, condensed, context-tailored, pragmatic, and direct information sharing is needed to fill in the farmers' knowledge gaps on each adaptation measure, one by one. This study provides such information to support decision making on the implementation of irrigation, by acknowledging the underlying uncertainties.

In arid regions drought causes repeated, anticipatable Y_{Loss} for field crops (Siebert and Döll, 2010) and hence, irrigation is a straightforward means to mitigate otherwise inescapable Y_{Loss}. As a country of hundreds of thousands of lakes and rivers, Finland has exceptional water reserves close to the field parcels which can be used for irrigation (Peltonen-Sainio et al. 2015b). This ecosystem service has not encouraged farmers, except momentarily in the 1970 s, to use irrigation to mitigate likely Y_{Loss} caused by drought (Suppl. S5 and S11). As an example of the most extreme cases, the low precipitation severely limited yields in virtually all sub-regions of the southwestern study region in Finland in 1971, 1973, 1975, 1976, 1986, 1989, 1992, 1994, 1999, 2001, 2006 and 2019 (Fig. 3 and Suppl. S5). On the other hand, it did not limit the yield formation in virtually any of the sub-regions in years such as 1996, 1998, 2002 and 2015. This long-term data focussed on the critical yield determination phase has highlighted that the years are not similar, and that this variability is likely to complicate farmers' decisions. The future projections have the similar feature with high differences between the growing seasons (Suppl. S7 and S9). Furthermore, the future mean precipitation (across 2041–2070) during the yield determination phase might shift either towards a slight reduction (Suppl. S9 and S10) or increase (Suppl. S7 and S8) depending on climate model. Hence, critical early summer droughts will not necessarily ease off or get dramatically worse. On the other hand, higher winter precipitation may increase soil water storage available in the late spring and early summer (Puustinen et al. 2007, Ruosteenoja et al. 2017), but elevated temperatures (Ruosteenoja et al. 2016) may again increase evapotranspiration and soil drying. Furthermore, precipitation may come more frequently in downpours (Lehtonen et al. 2014, Scoccimarro et al. 2015), which may increase the surface runoff (Puustinen et al. 2007, Warsta et al. 2014) and reduce water-productivity. Thereby, estimated future precipitation may not meet the likely increasing crop requirement for water availability (Ylhäisi et al. 2010), even though the rising atmospheric CO_2 concentration may increase crop water productivity (Deryng et al. 2016).

4.2. Breaking the baggage of the past reservations towards irrigation?

In the light of the results of this study, future precipitation is not likely to change to such an extent that the change *per se* would strongly encourage farmers to start implementing new forms of irrigation - especially when coupled with the high variability in conditions. In addition to the uncertainty regarding weather conditions, cereal markets and prices are volatile and make the planning of any investment challenging for a farmer. Nonetheless, the farm size may continue to increase in Finland as has been the case in the past (e.g., farms of > 100 ha have increased from 788 in 1995 to 5,725 in 2019) (Luke 2020), which may substantially increase the farm-scale total Y_{Loss} caused by drought.

Based on estimations of the cost savings due to irrigation in times of drought in the recent decades (1991–2020), two sprinkler systems were found to be viable options for spring cereals, but only in the case of larger farm sizes and larger farm-scale yield levels (Table 1). In these cases, the expected savings from drought damage mitigation exceeded the investment and operation expenses of irrigation. The number of large farms has substantially increased during the last decades. Hence, in the future irrigation may be viable option for higher number of farms than before. Drought damage mitigation itself was not estimated to be sufficient to cover the investment costs of subsurface irrigation, even though our calculation included the current government-issued agricultural investment subsidies of 40%. The irrigation system however provides additional benefits beyond irrigation. These include drainage and mitigation of damage caused by excess water and flooding (Wesström and Messing 2007, Österholm et al. 2015, Carstensen et al. 2019). Hence, considering both services is likely to increase the feasibility and the farmer's readiness to invest in such an expensive subsurface system.

In the light of estimations of the avoided costs, the incentive to invest in irrigation may largely depend on the farm size and yield level. Interestingly, the farmers with large farms were the most cautious regarding the uncertainties in the implementation of irrigation and they also considered irrigation systems to be too expensive (Peltonen-Sainio et al. 2021). Thereby, it is evident that large farms should be the key-target group of farmers for knowledge sharing efforts. Considerations of any future use of irrigation in high-latitude conditions call for transparent information like the information provided in this pragmatic study on costs and benefits. In the case of indisputable indications of more frequent dry spells in the future, climate change *per se* would speed up transition from rainfed agriculture towards irrigated agriculture, but this is not likely in the light of our future precipitation estimations. Hence, the quantitative and novel data of this study may serve as an initiative to consider a shift from past reservations against irrigation and start considering irrigation as a possible measure to mitigate production uncertainties and yield variability which are characteristic to high-latitude agriculture. The outcomes of this study are not useful only for farmers alone, but also for policy makers when considering future incentives for investments, not least because the variation in precipitation and early summer droughts not only impacts production and production certainty but also has many environmental impacts including higher risks for erosion, nutrient leaching and damaged soil structure.

4.3. Uncertainties in estimations

The uncertainty related to future climate projections involves the natural variation in the climate, the uncertainties of future emissions, modelling uncertainties, and the uncertainty of human action and nature's ability to adapt to the changing environment. Ruosteenoja et al. (2016) researched climate simulations for the ongoing 21st century using 28 CMIP5 models forced by the RCP forcing scenarios. In Finland the multi-model mean change in the June precipitation for the 2040–2069 period relative to 1981–2010 was approximately + 7% in both RCP4.5 and RCP8.5 scenarios, the changes ranging under the RCP4.5 between −10 and + 22% and under the RCP8.5 between −11 and + 25%.Hence, changes in June precipitation are uncertain, although most models project slight increases. This uncertainty was well represented in our precipitation projections, in which the changes in the mean June precipitation ranged between −5% and + 30%.

We used a straightforward method to estimate the past Y_{Loss} caused by droughts (Fig. 2), which resembled the decision-making grounds of a farmer based on observed and forecasted precipitation and their demonstrated impacts on cereal grain yields in the study region according to the long-term data (Peltonen-Sainio et al. 2011). Farmer's decisions may be further supported by local weather forecasts, on-farm weather station(s) and measurements of soil water content. However, sophisticated decision support systems for the estimation of Y_{Loss}, e.g., based on hydrologic and crop models are still under development considering their usability for farmers and they exhibit uncertainties, if they are not well calibrated for local conditions or fail on more general aspects. The estimated mean Y_{Loss} for each year was compared to the observed difference between the yearly and decadal mean yields in the region (data not shown). This consistence test indicated that Y_{Loss} was overestimated by some 90 kg/ha, which is likely to be attributable e.g., to compensation caused by favourable conditions later in the growing season (i.e., through higher grain weight) (Peltonen-Sainio et al. 2007). Abundant rains right before the critical yield determination phase may have alleviated the impacts of low precipitation during this phase as well. Furthermore, in 27% of the years the estimated drought induced Y_{Loss} was 635 kg/ha lower than observed as an average. This may have been caused by some other yield reducing constraint(s) (Peltonen-Sainio et al. 2016c). These comparisons highlighted how variable conditions during the growing season are apt to challenge a farmer when trying to cope with the various stressors and understand their contributions to the experienced Y_{Loss} (Peltonen-Sainio et al. 2016c).

A sensitivity analysis was used to study how uncertainties could affect the outcome of the estimations of cost-efficiency used in this study. Parameter values used in the CBA-model (baseline) were further adjusted to test the sensitivity to changes in interest rates, efficiency coefficients, crop price development, and their interaction. More conservative assumptions reduced the expected *NPV* of each irrigation system. Under these changed assumptions stationary irrigation system was the only irrigation method that on average yielded a positive *NPV* (Table 2). In the combined high interest and low irrigation efficiency scenario the results were similar. More optimistic price development made the average *NPV* of self-propelled irrigation positive, but just barely. The decision-making rule of CBA is that one should implement only systems with a positive *NPV*, i.e., when the discounted benefits exceed the discounted costs (Pearce et al. 2006). Hence, stationary irrigation system was found to be the most potential system to adapt to high latitudinal droughts which occur at the most critical phase for yield determination of spring cereals. The scope of the CBA was to support farmer's decision making. Hence, before implementing the outcomes to the study region, more comprehensive CBA is needed to consider externalities, such as possible water scarcity in time of irrigation and limitations caused by water quality.

Table 2
Outcomes of the sensitivity analyses where parameters used in the CBA-model (baseline) were changed: interest rate (from 0.03 to 0.06), efficiency coefficient of irrigation (from 100% to 90%) crop prices (from 0.007 to 0.015) and cross-effect of interest, crop prices and efficiency coefficient. *NPV*, the net present value.

Irrigation system	Average *NPV* (1000 €/farm)
Baseline:	
Self-propelled irrigation system	−40 €
Stationary irrigation system	−1 €
Subsurface irrigation	−480 €
Interest rate changed:	
Self-propelled irrigation system	−42 €
Stationary irrigation system	−7 €
Subsurface irrigation	−495 €
Crop price development changed:	
Self-propelled irrigation system	−29 €
Stationary irrigation system	**11** €
Subsurface irrigation	−468 €
Efficiency coefficient changed:	
Self-propelled irrigation system	−45 €
Stationary irrigation system	−6 €
Subsurface irrigation	−485 €
Efficiency, crop price development and interest rate changed:	
Self-propelled irrigation system	−38.5
Stationary irrigation system	−3.5
Subsurface irrigation	−491.5

5. Conclusions

This retrospective study highlighted that irrigation would have been cost-efficient in the most drought-prone region of Finland in the case of large farm size with high yield levels. However, projected changes in future precipitation would not substantially affect the critical yield determination phase of spring cereals when considering the uncertainties of the projections. Hence, the change in precipitation *per se* would not necessarily further encourage farmers to invest in irrigation, as it may appear that the potential Y_{Loss} would be quite comparable to those experienced in past times. However, farms have become substantially larger, and our results indicate that sprinkler irrigation systems would be feasible, especially in the case of large farms and farm yield levels that are above the current mean. This study quantifies for the first time the interannual and within region variability in Y_{Loss} for the past five decades (1971–2020) in the most drought prone area of Finland. This data coupled with estimations of the economic feasibility of irrigation systems for the recent past (1991–2020) may act as an opening move to deliberate moving from the rainfed *status quo* and to start considering the role of irrigation as a key measure to reduce production uncertainties and yield variability in high-latitude conditions. As early summer droughts not only impact production *per se* but also have many environmental impacts like increasing risk for nutrient leaching, the costs and investment needed for adaptation to weather constraints like early summer droughts should not be payable only by farmers, and hence the results of this study are also for the use of policy makers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2021.100334.

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