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Varietal adaptations matter for agricultural water use – a simulation study on grain maize in Western Switzerland

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ABSTRACT

Climate change is altering agricultural production conditions. Adaptation measures to reduce negative impacts of climate change and utilize emerging potentials may involve the increased use of irrigation water. With increased irrigation water consumption, water use conflicts and resource constraints may occur and aggravate under climate change. Estimates of expected changes in irrigation water demands are of great value to anticipate if and where such issues may arise. This study presents an analysis of projected changes in irrigation water demand and grain yield of maize subject to variation in cultivar choice, sowing dates, soil depth and texture, as well as climate projection uncertainty and crop model parameterization uncertainty. Study results suggest that varietal choice opens up a large scope for adaptation of future grain maize productivity with important implications for agricultural water use. Assuming that no mitigation measures are taken (RCP8.5), the cultivation of late-maturing varieties in combination with earlier sowing can be considered a suitable adaptation choice, even allowing for increasing yield levels until mid-century. However, with this adaptation choice, irrigation water demands could be expected to increase by up to 40% until the end of the century. While absolute estimates of irrigation water demands are strongly dependent on soil depth (and to a much smaller degree on soil texture), change signals of irrigation water demands were largely unaffected by variation in soil parameters. However, estimates of future changes in irrigation water demands are subject to large uncertainties originating from climate projection uncertainties, implying possible increases in irrigation water demands between < 10% and > 60%. Increases in irrigation water demands could be constrained by cultivating early-maturing varieties at the expense of lower production potentials. Selection and breeding efforts steered towards early varieties with extended grain filling duration may help to increase yield potentials.

1. Introduction

Climate change is altering agricultural production conditions. Increasing temperatures have various implications for plant growth and crop productivity. Warmer temperatures lead to an extension of the growing season, potentially benefitting agricultural productivity – especially in temperate regions of the world, where growth temperatures for many crops are currently below optimum and water limitations play a minor role. However, increasing frequencies of heat and drought extremes are expected to have detrimental effects on agricultural productivity also in temperate regions of Europe (e.g. Olesen et al., 2011; Žalud et al., 2017; Mäkinen et al., 2018; Grillakis, 2019). Possible measures of agricultural adaptation to prevent negative impacts of climate change and utilize emerging potentials are changes in cultivars, crops and increased use of irrigation water (Bindi and Olesen, 2011). It can be expected that farmers will take appropriate actions autonomously, provided they have access to required resources (e.g. financial means to invest in irrigation infrastructure, access to water resources, knowledge of suitable crops, cultivars and farming techniques, access to adapted seeds and technical equipment; Leclère et al., 2013). In most European countries (especially Northern Europe), adaptive capacity is considered to be and remain high (Iglesias and Garrote, 2015; Reidsma et al., 2009; Williges et al., 2017). As farmers adapt their management in response to changing climate (and other) drivers, negative environmental impacts may be aggravated and/or resource conflicts might emerge. For example, negative impacts of climate change on biodiversity and water quality may be aggravated by management adaptations supporting agricultural productivity

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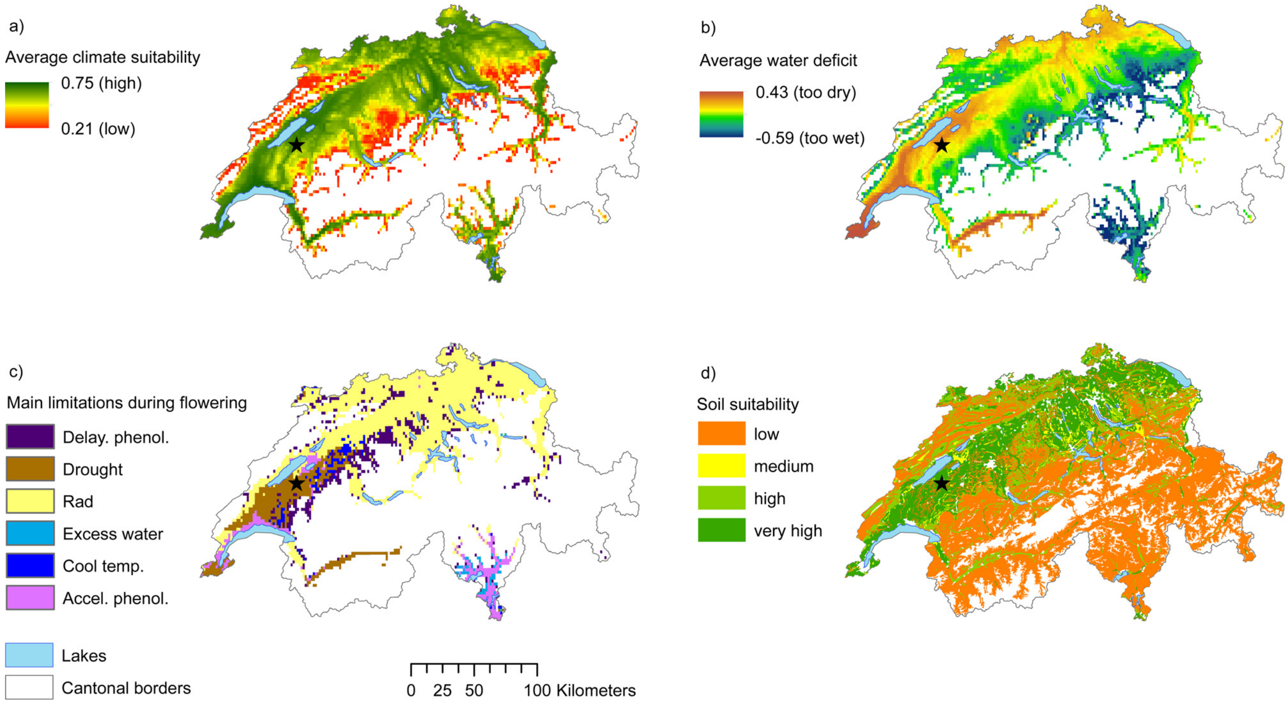

Fig. 1. Study site location in Switzerland with background information on average climate suitability for grain maize (a), average water deficit limitations for grain maize (b), most frequent climatic limitations for grain maize (c), and agricultural soil suitability (d). Sources of data: BFS 2012, Holzkämper et al. 2015b.

(Papadimitriou et al., 2019). Increased abstractions of irrigation water from groundwater sources may lower the groundwater levels with possible negative implications on drinking water availability and quality (Neset et al., 2019).

Crop growth models fed with climate projection data from global and regional climate models are common tools for anticipating climate change impacts on crop productivity and changes in irrigation water demands. For estimating emerging threats of maladaptation, such models can be applied on the basis of varying assumptions about possible management adaptations. If evaluated in combination with a range of climate projections, the benefits of alternative adaptation options for securing productivity and estimate future water demands can be assessed. By matching changing water demands with changes in resource availabilities, emerging water use conflicts can be anticipated. On the basis of such study findings, regulations and incentive systems may be adapted to prevent possibly emerging maladaptive responses to climate change.

Many previous studies analyzed current and future water demands for irrigation in Europe and at the global scale (e.g. Wriedt et al., 2009; Schaldach et al., 2012; Boehlert et al., 2015; Konzmann et al., 2013). Projected changes can differ substantially between studies. For the Swiss Rhone Valley, Smith et al. (2014) estimated increases in irrigation water demands of 15% for grassland and 30% for grain until mid-century, subject to large climate projection uncertainties (even after bias-corrections). In a regional evaluation, Fuhrer et al. (2014) estimated an increase of irrigation water demands by 4-16% in the Swiss Rhone Valley until 2050. Discrepancies in projected changes can be attributed to structural impact model uncertainties, climate projection (and downscaling) uncertainties, as well as differences in crop choice and underlying assumptions about varieties, management and site conditions (i.e. soil parameters).

Systematic studies of uncertainty sources contributing to projection uncertainty in changing irrigation water demands have recently been conducted by Elliott et al. (2014) and Webber et al. (2016). Elliott et al. (2014) compare ensembles of water supply and demand projections on the basis of 10 global hydrological models and six gridded crop models. Webber et al. (2016) explored the effects of structural model uncertainties (i.e. variation in model components) on estimates of maize crop water use and risk of crop failure.

Such projection uncertainties imply decision risks for adaptation planning: if more water is required, existing irrigation infrastructure may not be sufficient to provide the required amounts of water or water resources may be overused with negative implications on the environment and other water users. Besides consideration of impact model uncertainties, recent studies have also called for the inclusion of multiple varieties when estimating impacts of climate change on crop productivity – accounting for the possibility of climate change adaptation efforts (e.g. Rezaei et al., 2018; Parent et al., 2018).

This study presents an extensive uncertainty analysis of projected changes in irrigation water demand and grain yield of maize cultivated in Switzerland considering climate projection and crop parameterization uncertainty, while accounting for regional variation in soil texture and depths and possible shifts in sowing dates, varietal choice. The following research questions are addressed:

- What impacts of climate change on crop productivity and irrigation water demands do we have to expect?
- How do projected impacts vary depending on shifts in varietal selection and sowing dates?
- How do projected impacts vary with soil depth and texture?
- What are main sources of uncertainties in projected changes?

The study results add to the understanding of key drivers of change and provide relevant information for robust decision-making in context with climate change adaptation planning in Switzerland.

2. Study region

The study is conducted in the South-Western part of the Swiss Central Plateau with the station of Payerne being the reference site for our considerations of climate change impacts in this region (Fig. 1). Due to its favourable pedo-climatic conditions, this region is important for agricultural production in Switzerland (BFS, 2012; Holzkämper, 2015b). Considering impacts of climate change on crop productivity at

Table 1
Soil profiles descriptions for three texture types with 120 cm depth; for 70 cm depth only the first three layers were considered.

Layers	thickness [m]	sand [%]	clay [%]	OM [%]
Sandy loam				
1	0.2	56	14	4.5
2	0.1	57	11	2
3	0.4	60	10	1
4	0.2	57	10	0
5	0.3	65	12	0
Silt loam				
1	0.2	36	14	4.5
2	0.1	37	11	2
3	0.4	40	10	1
4	0.2	37	10	0
5	0.3	45	12	0
Clay loam				
1	0.2	36	34	4.5
2	0.1	37	31	2
3	0.4	40	30	1
4	0.2	37	30	0
5	0.3	45	32	0

the global scale (great production losses estimated for tropical and subtropical regions; benefits in northern latitudes), it is possible that Swiss agricultural production may gain importance in an international context in the future. However, this region is also regularly experiencing drought limitations today (Holzkämper et al., 2015b) and these limitations are expected to increase with future climate change (Klein et al., 2014). Autonomous adaptation is on the way through the formation of irrigation cooperatives. Also, large irrigation infrastructure developments are being established in the region. To prevent maladaptive responses (e.g. resource exploitation/water use conflicts), information on likely changes in irrigation water demand is essential for this region in particular.

3. Method

The generic crop model CropSyst (version 4.13.09; Stöckle et al., 2003) has been applied in this study. CropSyst simulates daily biomass accumulation in response to soil, climate and management drivers. Daily biomass growth is calculated as the minimum between radiation-dependent growth (Monteith, 1977) and transpiration-dependent growth (Tanner and Sinclair, 1983). Transpiration-dependent growth can be limited by soil water availability. To estimate plant water uptake, the soil profile is divided into multiple layers. The uptake from each layer is estimated on the basis of the water potential difference between the soil and the plant xylem, multiplied by plant conductance (mainly determined by root conductance). Soil water dynamics are simulated based on the daily cascade approach implemented in CropSyst (Stöckle and Nelson, 2000).

Within this study, CropSyst was applied on the basis of a crop parameterizations for grain maize from Holzkömper et al. (2015c), calibrated using the procedure described in Klein et al. (2012). To allow for the quantification of crop parameterization uncertainty, 9 parameter sets (produced based on the stochastic calibration routine) were used here. Parameter values of the 9 parameter sets can be found in the Supplementary material.

The crop model estimates were validated based on recent statistical yield data for the period 2009-2017, confirming satisfactory performance for the simulation of grain maize yield levels and variability (Willmott-index of 0.65 + -0.14; see Supplementary for full list of performance metrics).

To account for possibilities of varietal adaptation, growing degree day (GDD) requirements to reach flowering were adapted in accordance with findings about variations in cycle duration across Europe by Parent et al. (2018), who found that thermal time to flowering varied between 700 and 1200 due to genetic variation amongst 121 maize accessions. For this study, GDD's to reach the beginning of flowering (900 in the parameterization from Holzkämper et al. (2015c)) were therefore adjusted by + -200 to represent early and late maturing varieties, respectively. GDD requirements to reach the beginning of flowering were 700 for the early variety, 900 for the medium variety, and 1100 for the late variety. To reach maturity, 1650 GDDs were required for the early variety, 1850 for the medium variety and 2050 for the late variety. With this, we assume to represent a realistic range of varietal differences in lengths of vegetative phases within Europe.

Under current climatic conditions, the range of sowing dates in Switzerland varies largely between mid-April and mid-June (Hiltbrunner et al., 2014; Hiltbrunner et al., 2016; Hiltbrunner et al., 2018). Therefore, May, 10th (DOY 130) can be regarded as a suitable sowing date under current climatic conditions. Shifts towards earlier dates are considered realistic as possible adaptations to climate change. Based on these assumptions, the following sowing dates were selected to be tested in this study: DOY 70 (March, 11th), 100 (April 10th), 130 (May, 10th).

Automatic irrigation was specified to be triggered based on soil water depletion (0.5 maximum allowable depletion). The period of potential irrigation was defined in relation to phenological development: from the beginning of active growth to the onset of yield formation. If irrigation was triggered, between 15 and 25 mm of irrigation water were applied per day to refill soil water content to maximum capacity.

To account for regional variation in soil conditions in this study, six different soil profiles were defined based on NABO soil profile data (NABODAT, 2018): three texture types (sandy loam, silt loam and clay loam) with two soil depths (70 and 120 cm) and an organic matter content fixed at 4.5% in the top-layer. The three selected soil texture types are within the medium range of observed conditions in NABODAT (2018). The selected soil depth levels relate to the 60th and 95th percentiles of recorded usable soil depths recorded across Switzerland NABODAT (2018); they are indicative for soils with high to very high suitability for arable farming. Full information on texture parameters in all sublayers assumed for this study is summarized in Table 1.

Climate projection data was derived from CH2018 (2018), where EURO-CORDEX projection data had been statistically downscaled using the quantile mapping approach to preserve the daily granularity and transient nature of the native RCM simulations throughout the common simulation period 1981 – 2100. A subset of six downscaled GCM-RCM model chains were chosen from the CH2018 scenario dataset (Table 2).

Table 2
: Selected climate model projections.

Projection name	Regional climate model	Global circulation model	Spatial resolution
CLMCOM-CCLM4-HADGEM-EUR44	CCLM4-8-17	MOHC-HadGEM2-ES	EUR-44: 0.44 degree
DMI-HIRHAM-ECEARTH-EUR11	DMI-HIRHAM5	ICHEC-EC-EARTH	EUR-11: 0.11 degree
KNMI-RACMO-HADGEM-EUR44	KNMI-RACMO22E	MOHC-HadGEM2-ES	EUR-44: 0.44 degree
SMHI-RCA-CSIRO-EUR44	SMHI-RCA4	CSIRO-QCCCE-CSIRO-Mk3-6-0	EUR-44: 0.44 degree
SMHI-RCA-MIROC-EUR44	SMHI-RCA4	MIROC-MIROC5	EUR-44: 0.44 degree
SMHI-RCA-MPIESM-EUR44	SMHI-RCA4	MPI-M-MPI-ESM-LR	EUR-44: 0.44 degree

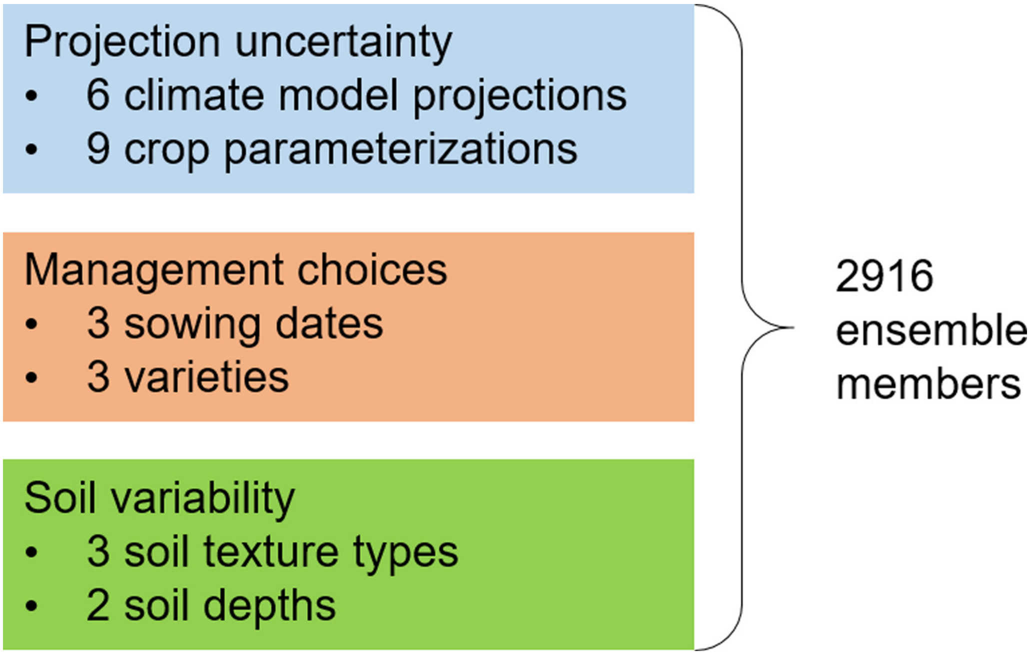

Fig. 2. Overview of simulation ensemble design.

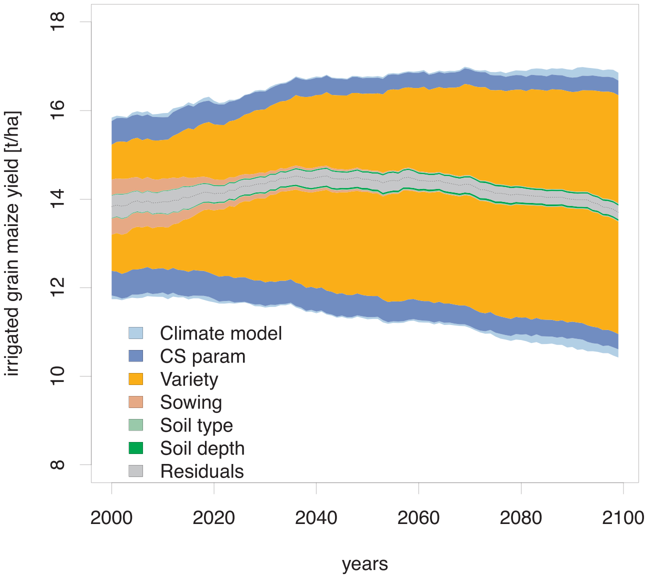

Fig. 3. Uncertainty bounds (5^{th}-95^{th} percentiles estimated over 20-year time window) of simulated grain maize yields and attributed uncertainty sources shown in colors.

The selection was based on the daily availability of all required meteorological parameters (temperature, precipitation, relative humidity, wind speed, and radiation). Only projections of emission pathway RCP 8.5 (no climate mitigation) were selected to study impacts greatest possible increases in irrigation water demands here.

The full simulation ensemble thus accounts for two types of projection uncertainty (i.e. climate projection uncertainty and crop model parameterization uncertainty), two aspects of spatial variability in soil properties (i.e. soil texture and depth), and two adaptation options (i.e. choice of variety and sowing date) (see Fig. 2).

Overall variance in simulated grain maize yields and irrigation water requirements estimated with this simulation ensemble was attributed to the factors shown in Fig. 2 using ANOVA-based variance partitioning as previously done in Yip et al. (2011) or Holzkämper et al. (2015c). In this procedure, sums of squares as derived with the ANOVA are divided by the total sum of squares to result in the proportions of explained variances in simulation outputs that can be attributed to the different model inputs. Only single factors and no interactive effects were considered here; all interactive effects are thus summarized as “Residuals”. The effects of interannual climate variability on simulation outputs were averaged out by conducting the variance partitioning based on 20-year mean yields and seasonal irrigation amounts. All statistical analyses were conducted using R (R Core Team, 2019).

4. Results

4.1. Irrigated yields

Projections of the whole ensemble suggest that estimated yield levels vary substantially (variation by 4-6 t/ha; Fig. 3). The variance is mostly attributed to the choice of variety and crop model parameterization. The contribution of climate projection uncertainty to variation in estimated yield levels is relatively small. However, the contribution of climate projection uncertainty is larger when looking at relative yield changes (Fig. 4). It is the largest source of uncertainty over the first two decades of the time series, suggesting a possibility of both small positive and negative yield changes in this period. In the near future, the choice of cultivar contributes increasingly to the variance in estimated yield changes – adding almost 20% variation by the end of the century. The choice of sowing date contributes increasingly to the variation in yield change signal with a maximum contribution of about 15% by the end of the century (Fig. 4). However, this has to be seen in relation to Fig. 3, which shows that the amount of variation in yield levels explained by shifts in sowing dates is reduced to almost 0 within the first few decades of the simulation period. This shows that the increased contribution to variance in yield changes originates from differences in reference yield levels due to shifts in sowing dates.

Crop model parameter uncertainty plays a minor role for yield change signals with a maximum contribution of 2% by the end of the century (Fig. 4). Variation in soil depth and soil texture is insignificant both for projected yield levels and yield change signals (Figs. 3 and 4).

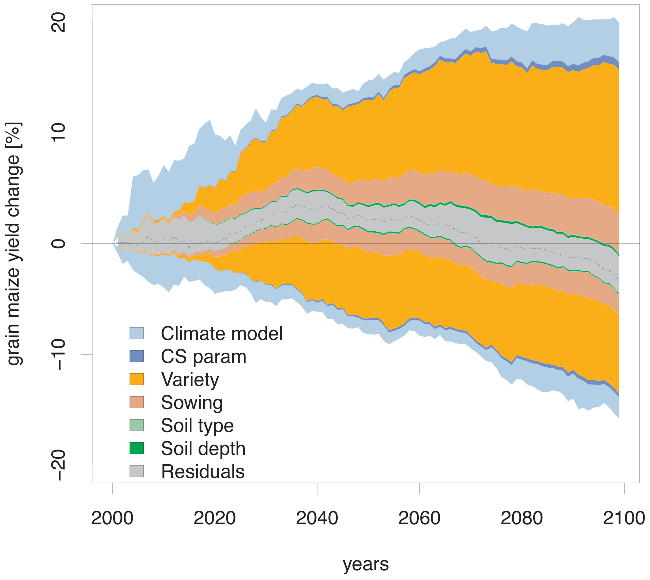

Fig. 4. Uncertainty bounds (5th-95th percentiles estimated over 20-year time window) of simulated grain maize yield changes in comparison to the reference period 1981-2000 and attributed uncertainty sources shown in colors.

4.2. Irrigation water demands

Ensemble estimates of seasonal irrigation water vary widely between 120 and 320 mm (Fig. 5). The uncertainty increases slightly towards the end of the century – mostly attributed to climate projection uncertainty. The largest part of variance in estimated irrigation water demand originates from the choice of variety over the whole simulation period. Choice of sowing date plays a minor role, but its contribution to variance in estimated seasonal irrigation needs increases slightly towards the end of the century. Soil parametrization and in particular, soil depth contributes considerably to variation in seasonal irrigation estimates (~50 mm). Crop model parametrization uncertainty contributes constantly, but little to overall variation (~30 mm).

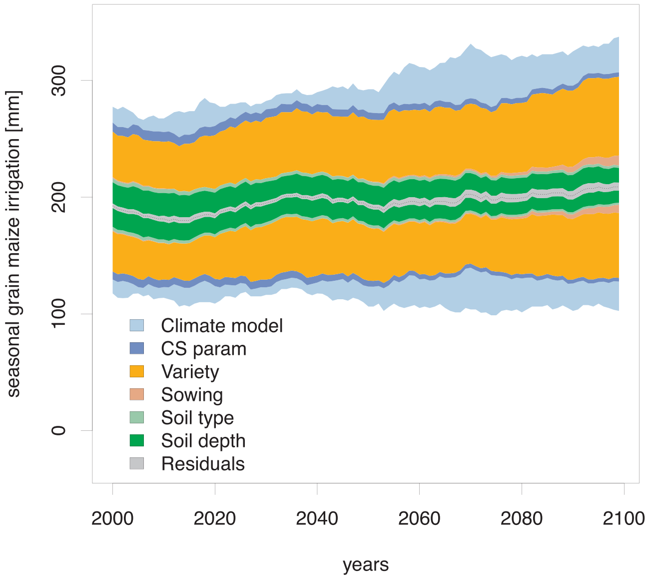

Fig. 5. Uncertainty bounds (5th-95th percentiles estimated over 20-year time window) of simulated grain maize irrigation needs and attributed uncertainty sources shown in colors.

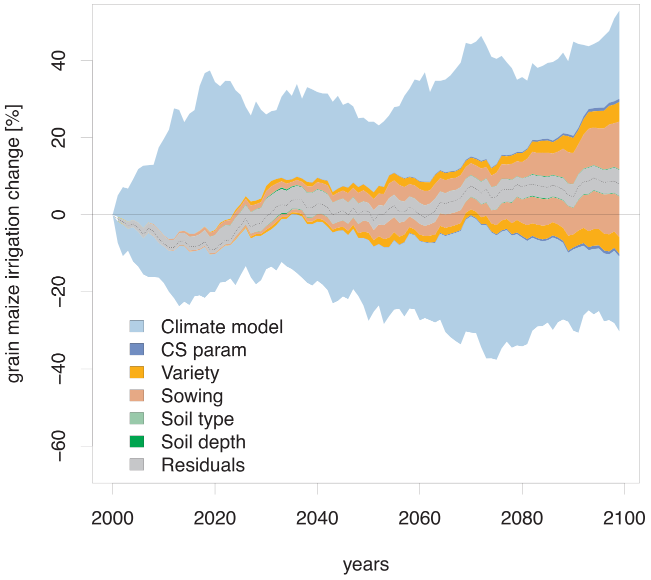

Fig. 6. Uncertainty bounds (5th-95th percentiles estimated over 20-year time window; dashed line indicates median) of simulated changes in irrigation water demands in comparison to the reference period 1981-2000 and attributed uncertainty sources shown in colors.

Variance in projected changes in irrigation water demands is clearly dominated by climate model projection uncertainty (Fig. 6). During the first few decades of the simulation period, a slight decrease in irrigation water demands is suggested by the median of the distribution, while a steady increase is suggested for the second half of the century. However, these estimates are subject to very large climate projection uncertainties and from 2020 onwards, also choice of sowing and variety contribute increasingly to variation in estimated changes in irrigation water demands.

Variation in soil depth and texture is found to play a negligible role for estimates of changes in irrigation water demands.

4.3. Scope for adaptation through choice of variety and sowing dates

In-depth analysis of simulation results for the three different varieties and three sowing dates considered in this study highlights the high sensitivity of estimated yield change signals to the choice of varieties and sowing dates (Fig. 7). Overall, estimated yield levels are largest with the late variety and lowest with the early variety. Yield levels estimated for the early variety are projected to decrease largely, irrespective of the selected sowing date (Fig. 7). Projections of the late variety suggest a possibility of increasing yields. The yield increase is most pronounced with late sowing, as under these conditions yield levels of the late variety are severely limited by the fact that thermal conditions during early decades of the simulation period often prevent full maturity. However, projection uncertainties are large – mostly attributable to crop model parameterization. Towards the end of the century, the risk of a yield decrease is also slightly increasing with the late variety and early sowing. With the medium variety, the crop model projects a small increase with late sowing (s130) with increasing uncertainty towards the end of the century – suggesting also a possibility of yield decline. With earlier sowing (s70, s100), the model projects stagnating yields until mid-century and a small and a decline thereafter until the end of century.

Variation in soil depth (and texture) contributes most to variance in estimated yield levels for the early variety, less so for the medium variety and has hardly any influence on variance in estimated yield levels for the late variety. This can be explained by the fact that for the early variety, the grain-filling period, during which irrigation water is no longer applied, is more likely to fall within the period of limited water availability. This water stress is limiting yields of the early variety more severely on the shallow soil than on the deeper soil.

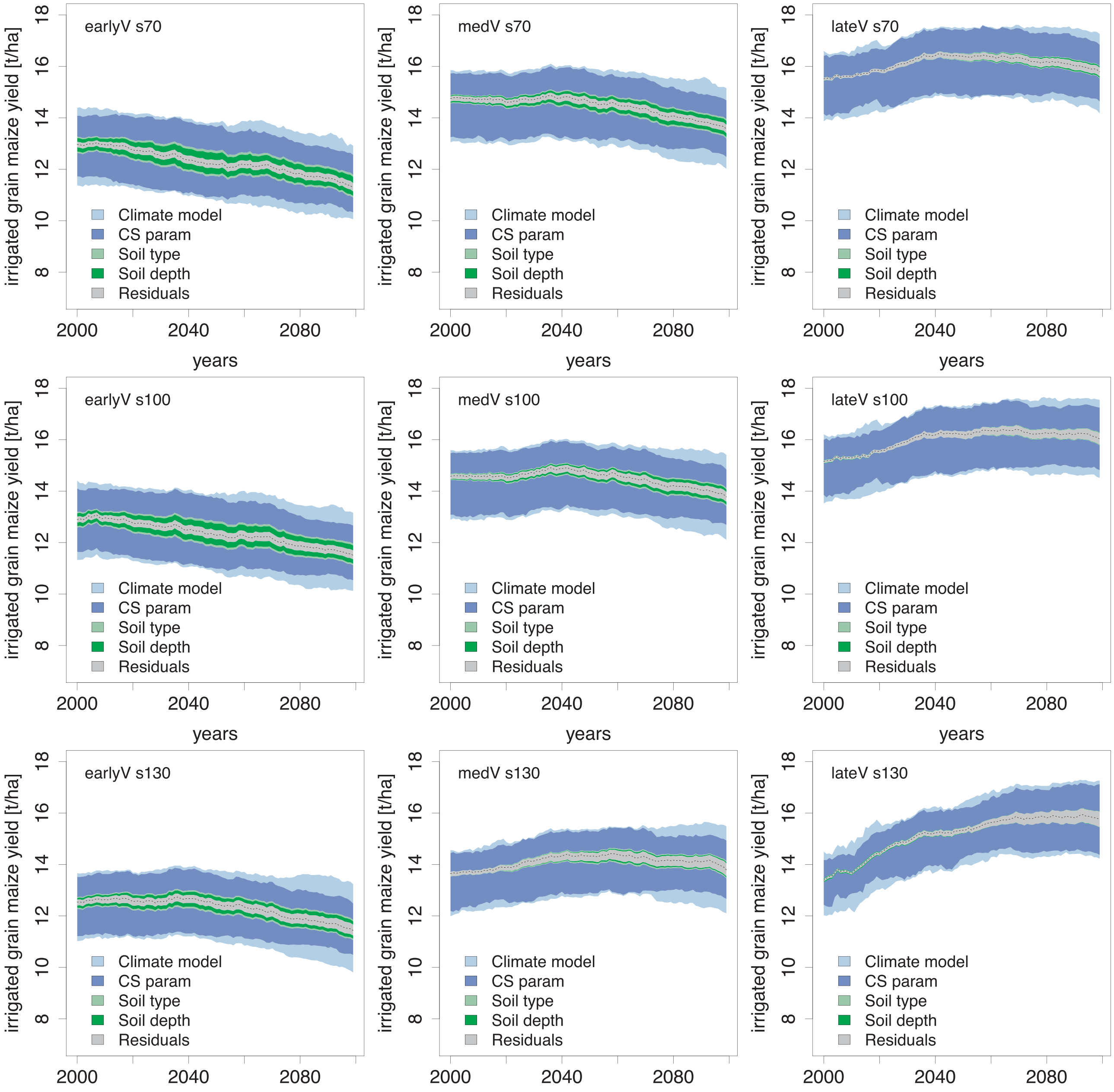

Fig. 7. Uncertainty bounds (5th-95th percentiles estimated over 20-year time window; dashed line indicates median) of simulated grain maize yields in comparison to the reference period 1981-2000 and attributed uncertainty sources shown in colors for all varieties (earlyV = early variety, medV = medium variety, lateV = late variety) and all sowing dates (s70 = 11 March, s100 = 10 April, s130 = 10 May).

Irrigation water demands are projected to increase most for the late variety with late sowing (39% median increase until end of century, Fig. 8). For the early variety, irrigation water demands tend to decrease or remain stable during the simulation period with early and medium sowing dates; with late sowing, a slight tendency towards an increase in irrigation water demands is noticeable for the early variety (+10 % until end of century). For the medium variety, irrigation water demands are projected to remain stable with early and medium sowing dates, but increase with late sowing (+20% until end of century). This increase in irrigation water demands with late sowing is connected to the fact that later sowing shifts the growing cycle further into the summer period during with water limitations are more frequent.

Climate projection uncertainty plays a similar role in projections for all variety and sowing dates. As also shown in Fig. 5, climate projection uncertainty contributes around 15% to variation in estimated irrigation water demands during the first half of the simulation period, increasing to 26% towards the end of the century. Crop parameterization uncertainty only plays a considerable role for projections of irrigation water demands of the late variety (at maximum 20%). For the early and medium varieties the contribution is 1-3% at maximum.

In contrast to simulated grain yields, simulated irrigation water demands are more strongly affected by soil depths. The contribution of soil depth to variation in estimated irrigation water demands is largely constant over the simulation periods and independent of variety and sowing dates (between 0.7 and 6% at maximum). The contribution of soil texture differences to variations in irrigation water demands is negligible (between 1 and 2.4% at maximum).

Irrigation water productivity, defined as the ratio between produced yield and applied irrigation water, is generally highest for the early variety and lowest for the late variety (Fig. 9). Over the course of the simulation, only minor trends are visible for the early variety, mostly attributable to shifts in sowing dates: with early sowing a slight increase

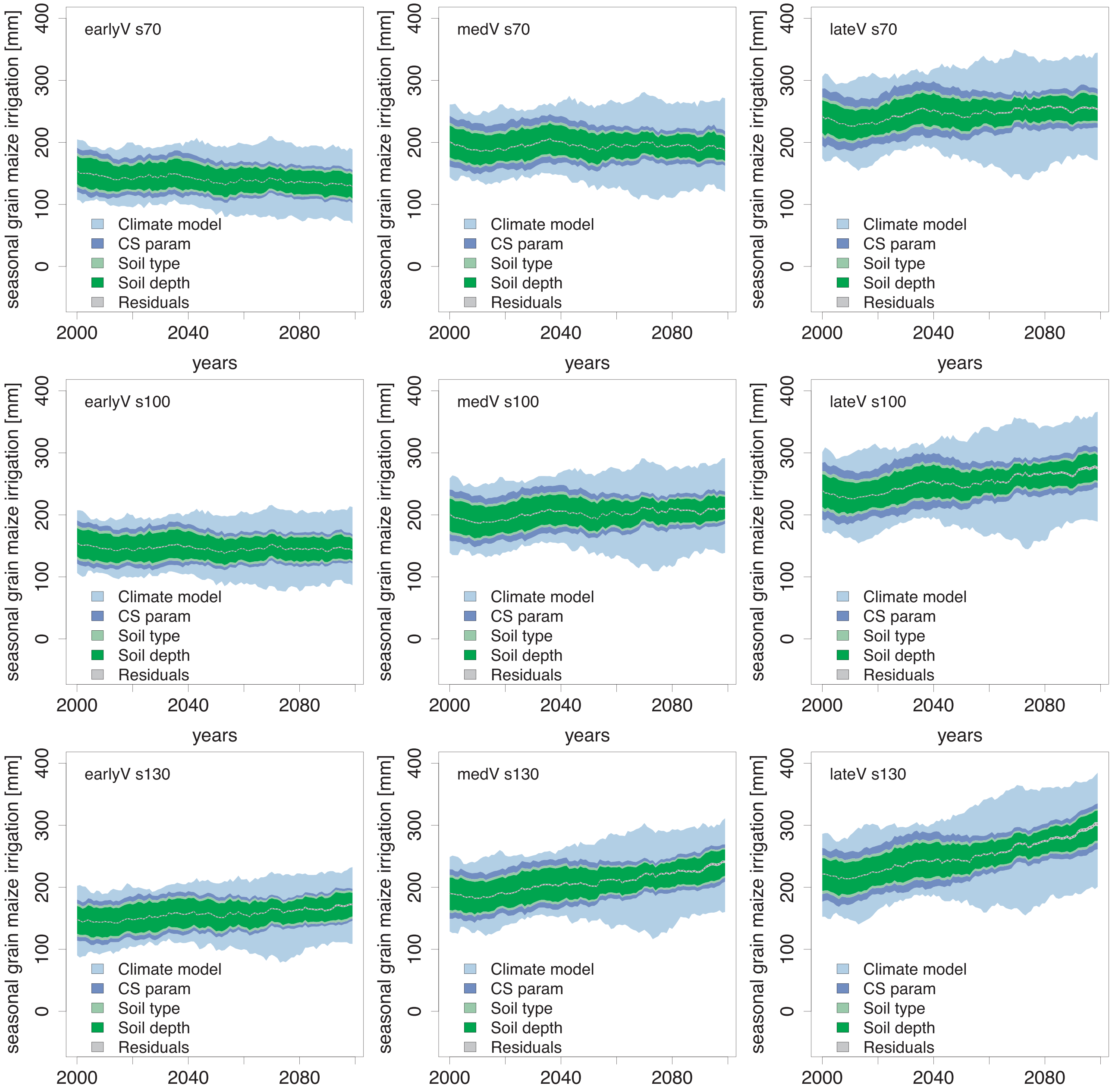

Fig. 8. Uncertainty bounds (5th-95th percentiles estimated over 20-year time window; dashed line indicates median) of simulated seasonal irrigation water demands in comparison to the reference period 1981-2000 and attributed uncertainty sources shown in colors for all varieties (earlyV = early variety, medV = medium variety, lateV = late variety) and all sowing dates (s70 = 11 March, s100 = 10 April, s130 = 10 May).

in irrigation water productivity is projected, while with late sowing, a decrease is projected. This can be explained by the fact that with earlier sowing, the growing cycle is shifted towards a period of the year with lower water limitations, while with later sowing the dependency on irrigation water inputs is increased.

5. Discussion

5.1. Changes in grain maize yield levels

A previous study by Webber et al. (2018) suggested that European maize yields are likely to decrease under climate change, if current genotypes and mix of irrigated and rainfed production would persist. In accordance with findings of the European study by Parent et al. (2018) and Zimmermann et al. (2017) and the recent global meta analysis by Aggarwal et al. (2019), our study results now confirm for Switzerland that yield potentials for grain maize could increase under climate change if adaptation is considered (i.e. irrigation, adapted sowing dates and growing cycles length). The late variety had generally higher yield potentials than earlier varieties due to the extended growing cycle, which allows for the accumulation of more biomass (see Supplementary material for more information on projected changes in growing cycle length). This beneficial effect is likely to lead to an increase in irrigated yield potentials until mid-century. Shifts in sowing date were found to matter less for estimated yields than varietal changes in this study. Earlier sowing is beneficial for crop productivity during the first half of the century, but the beneficial effect is diminished towards the end of the century. This can be explained by the fact that with early sowing the risk of yield loss through unsuccessful maturation (which is relatively high during the first few decades of the simulation period, especially for the late variety) can be reduced. Since this risk is generally reduced with increasing temperatures towards the end of the century, the

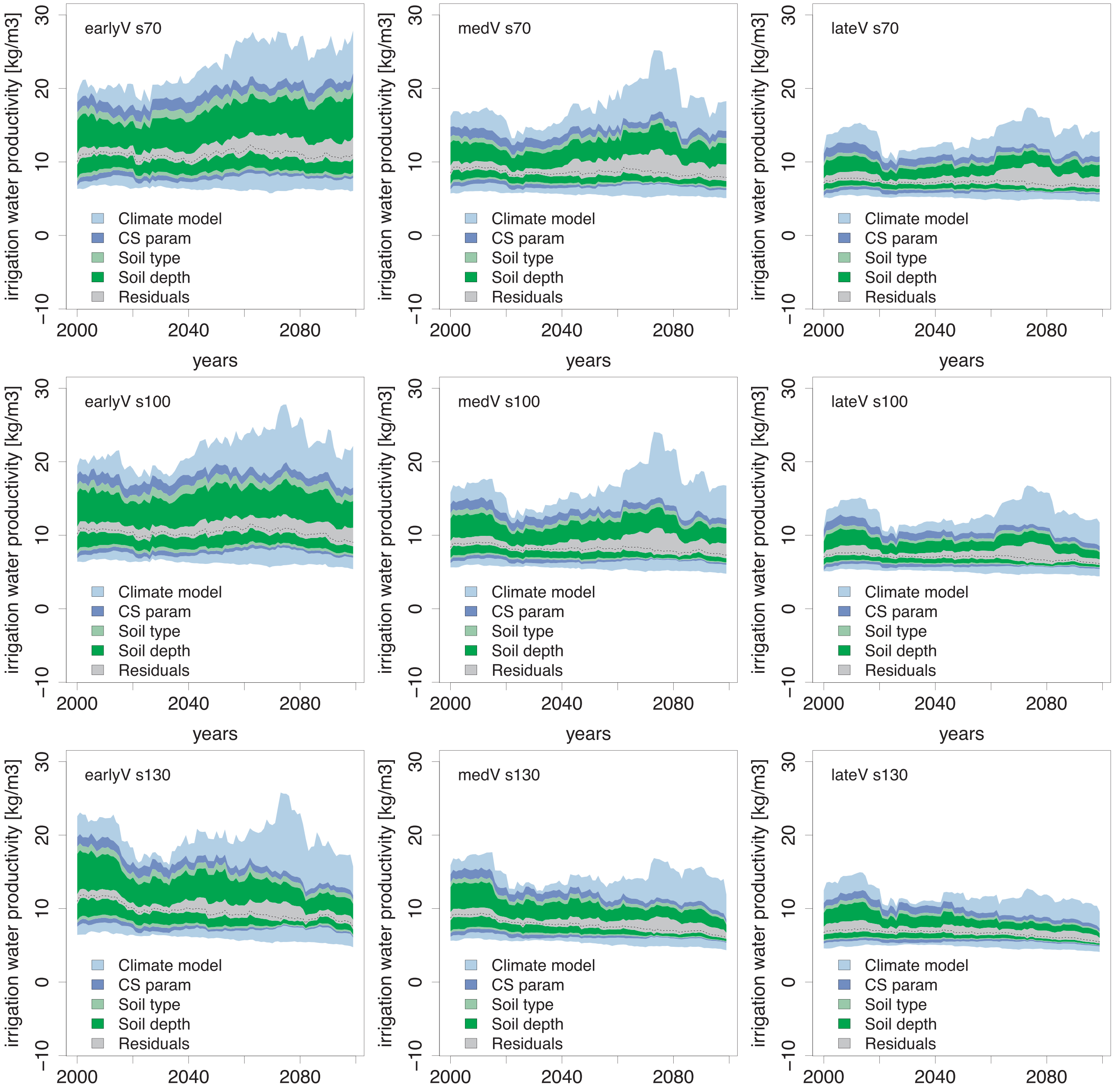

Fig. 9. Uncertainty bounds (5th-95th percentiles estimated over 20-year time window; dashed line indicates median) of simulated irrigation water productivity [kg/m3] in comparison to the reference period 1981-2000 and attributed uncertainty sources shown in colors for all varieties (earlyV = early variety, medV = medium variety, lateV = late variety) and all sowing dates (s70 = 11 March, s100 = 10 April, s130 = 10 May).

beneficial effect of earlier sowing on productivity is reduced with increasing projection horizon. This might imply a possibility for cultivating even later maturing varieties, which could be explored in future studies.

Variation in soil depth and texture was found to play a small role for absolute irrigated yield estimates and an even smaller role for estimated yield changes. For rain-fed yields, however, stronger impacts of texture and in particular soil depth could be expected as the available water content is strongly influenced by soil parameterization (e.g. Constantin et al., 2019).

The considerable contribution of climate projection uncertainty for estimates of yield change signals is not surprising and largely in line with findings from previous studies. For example, Finger et al. (2011) estimated positive and negative changes, subject to climate projection uncertainty. Holzkämper et al. (2015a) found that yield change estimates for grain maize in Switzerland were subject to large uncertainties, originating from both climate projection uncertainty and structural impact model uncertainty. Knox et al. (2016), who provided a meta-analysis of climate impacts on yields in Europe, also highlights that uncertainties in projected yield changes are large.

The influence of crop parametrization uncertainty on absolute yield estimates was found to be large here (Figs. 3 and 7). This finding is likely to be specific to this case study, as a previous study with a similar design by Tao et al. (2017) found that contributions of crop model parameterization and climate projection to total variance of ensemble outputs varied greatly among different crop models and also between sites. Given the availability of adequate data, future research aiming at refinements of crop model parameters might help to reduce this uncertainty source.

5.2. Changes in irrigation water demands for grain maize

In line with findings from previous studies at European level Webber et al. (2016), estimates of changes in irrigation water demands for grain maize were shown to be subject to large uncertainties, originating mostly from climate projections in this study.

Estimates of up to 40% increases in irrigation water demands by the end of the century are largely within the range of estimates previous studies. For example, Wada et al. (2013) estimated that irrigation water demands will considerably increase during the summer in the Northern Hemisphere (> 20% by 2100) under the highest greenhouse gas emission scenario (RCP8.5). For the Swiss Rhone Valley, (Smith et al., 2014) estimated increases in irrigation water demands of 15% for grassland and 30% for grain maize until mid-century, subject to large climate projection uncertainties (even after bias-corrections). In a regional evaluation, Fuhrer et al. (2014) estimated an increase of irrigation water demands by 4-16% in the Swiss Rhone Valley until 2050. Unlike these studies, our study suggests also possibilities of decreasing demands for irrigation water with some climate projections. This is most pronounced with model chain KNMI-RACMO-HADGEM-EUR44, but also apparent in SMHI-RCA-MIROC-EUR44. In these model chains, a high increase in temperature is projected in combination with an insignificant change in precipitation (annual and summer). With that, water limitations are generally reduced due to the shortened growing cycle with increased temperatures and smaller precipitation deficits in general. According to the ensemble medians, with late sowing, irrigation water demands could be expected to increase by 10%, 20%, and 30% for early-, medium-, and late-maturing varieties, respectively. With early sowing, irrigation water demands are projected to decrease by 22% and 11% for the early and late varieties, respectively, and remain unchanged for the late variety.

The effect of reduced water demands with accelerated phenological development that was identified here, had also been documented in previous studies (e.g. Yuan et al., 2016; Rashid et al., 2019). Such findings imply a possibility for limiting future crop water demands through adaptations of the growing cycle. Selecting for longer grain filling duration amongst early maize varieties could support the breeding of new (early-maturing) varieties with higher yield potentials (e.g. Gasura et al., 2014).

In response to increasing CO_2 concentrations, irrigation water demands may be lower than estimated in this study. This can be expected since it is generally assumed that transpiration rates decrease with increasing CO_2 concentrations as leaf stomatal conductance is suppressed. In the German FACE experiment by Manderscheid et al. (2014), it was found that maize water use efficiency can increase substantially with increased CO_2 concentrations under drought conditions. This increase in water use efficiency can however be alleviated under irrigated conditions as found by Meng et al. (2014). Also, at the plant- and canopy level, an increase in leaf area as a result of stimulated biomass growth at elevated CO_2 concentrations could compensate the reduction in leaf-level transpiration (Manderscheid et al., 2016). Due to complex interactions involved in crop responses to elevated CO_2 concentrations, which are currently not well understood, projections of responses to future CO_2-levels are still highly uncertain (e.g. Durand et al., 2018; Kellner et al., 2019). Further experimental studies of crop responses (with regard to yield, but also water use, root development, phenology) to elevated CO_2 in interaction with other factors is essential to reduce this projection uncertainty.

For this study, specifications of irrigation management were chosen in alignment with suggested defaults to quantify potential crop irrigation demands. They do not reflect realistic management settings. Different specifications would result in different absolute estimates of yield and irrigation water demands. Further research could explore how irrigation schedules could be optimized to achieve maximum irrigation water productivity.

5.3. Scope for adaptation through choice of variety and sowing dates

Despite considerable uncertainties, results presented in this study clearly suggest that the cultivation of late-maturing varieties of grain maize could benefit grain maize productivity under climate change. Until mid-century, yield potentials could be increased on the basis of such varietal adaptations and production potentials could largely be maintained until end of century, given a steady increase in the supply of irrigation water. In general, the cultivation of late-maturing varieties implies higher irrigation water demands, as the growth cycle is extended into the drought-prone period of the year (see Supplementary material for more detailed information on projected changes in growing cycle length and seasonal transpiration by variety and sowing date). Given the higher yield potentials of these varieties, it could be expected that farmers will choose to cultivate them if water resources for irrigation are available in sufficient amounts and at adequate costs in relation to the market prices to be achieved for grain maize.

While increased irrigation water application to prevent productivity losses under climate change is an adaptation measure with potential co-benefits for other ecosystem services such as soil regulation, nutrient cycling or carbon sequestration, it also implies a risk of water resource exploitation and water use conflict.

Based on global ensemble simulations of water supply and demand by Elliott et al. (2014), it was found that in regions such as Europe, surplus water supply could in principle support a net increase in irrigation, although substantial investments in irrigation infrastructure would be required. For Switzerland, it is expected that local and regional water shortages will become more likely under climate changes, as low summer discharge will coincide with higher water demands for irrigation (Brunner et al., 2019). Thereby the greatest water limitations for irrigation are expected in the South-Western part of the Swiss Central Plateau, where the city of Payerne is located. Natural lakes may serve as alternative sources of irrigation water, where river discharge is limited. Integrated modelling studies considering linkages between plant growth, agricultural water demands and water resource availability are suitable to study such questions of water use conflicts in depth.

However, large alternative irrigation water resources such as natural lakes may not be equally accessible in all arable regions with a high and ever-increasing production potential. One possibility identified in this study could lie in the cultivation of early maturing varieties. Such varieties would be preferable due to their ability to reach maturity (or pass drought-sensitive phenological phases) before seasonal water deficits occur. This effect of drought avoidance is supported by shifts towards earlier sowing dates. Early sowing provides benefits for irrigation water productivity in general (irrespective of varieties). Both these options could imply additional benefits in terms of heat stress avoidance – an effect that is not accounted for in CropSyst.

Which management options future farmers will choose depends not on climate conditions alone. Market prices, costs and agricultural policies will have important influences on future farming systems. Considering projected climate change impacts on agricultural production potentials at the global scale, which suggest a general potential of production increases in the temperate regions, it may be anticipated that the relevance of agricultural production may increase rather than decrease in these regions. Intensification of agricultural management may follow from such socio-economic change. This could lead to extension of irrigation area and increased abstraction rates – not only to satisfy increasing water demands of presently cultivated crops, but also for the cultivation of new, water-intensive crops with high added value (e.g. fruits and vegetables). To prevent exploitation of water resources, negative impacts on aquatic biodiversity and limit water use conflicts under scenarios of agricultural intensification, detailed studies on the future vulnerability of regional water resources to irrigation water abstractions are needed.

Varieties recommended for Switzerland correspond largely to early/

medium-varieties considered in this study. However, during the warm years of 2017/18, a tendency towards later maturing varieties was observed, which supports the findings of this study (Hiltbrunner, *personal communication;* Strigens, *personal communication*). Current sowing practices favor rather late sowing (between mid-April and mid-June). According to results presented here, earlier sowing could be beneficial in terms of water productivity gains and better utilization of growing season already under current conditions. However, suboptimal soil temperatures during this early period of the year could prevent a good plant establishment during early growth stages and increase weed pressure and the plants' susceptibility to pest and diseases (Hiltbrunner, *personal communication*). Such effects were not accounted for in this study and should be investigated in more detail in future studies.

6. Conclusions

It was demonstrated that a large scope for adaptations of future grain maize yield productivity in Switzerland exists through varietal choices available in Europe today. Impacts of climate change on changes in grain maize yields and irrigation water demands depend strongly on varietal choices and are also influenced by the choice of sowing dates. For early maturing grain maize varieties, yield declines would have to be expected under climate change, assuming that no mitigation measures were taken (RCP8.5). Under these conditions, the cultivation of late-maturing varieties in combination with earlier sowing can be considered a suitable adaptation choice to prevent yield declines for grain maize, which would even allow for increasing yield levels until mid-century. However, with this adaptation choice, irrigation water demands could be expected to increase by up to 40% until the end of the century. While absolute estimates of irrigation water demands were strongly dependent on soil depth (and to a much smaller degree on soil texture), change signals of irrigation water demands were largely unaffected by variation in soil parameters. However, estimates of future changes in irrigation water demands are subject to large uncertainties originating from climate projection uncertainties, implying possible increases in irrigation water demands between < 10 and $> 60\%$.

Increases in irrigation water demands could be constrained by cultivating early-maturing varieties at the expense of lower production potentials. Selection and breeding efforts steered towards early varieties with extended grain filling duration may help to increase yield potentials.

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 material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106202.

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