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ORIGINAL ARTICLE

Spatial and temporal trends in agro-climatic limitations to production potentials for grain maize and winter wheat in Switzerland

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Abstract Climate is a major driver of agricultural production potentials. To make the best use of these potentials, agricultural management should be adjusted to local climatic conditions. As these conditions change over time, understanding climatic limitations and their trends in time and space is essential for the planning of suitable adaptation measures. In this study, we provide a detailed spatio-temporal analysis of climatic yield potentials for grain maize and winter wheat in Switzerland. We find that current climatic suitability for grain maize is mostly limited by sub-optimal temperatures, radiation and water scarcity, while climatic suitability for winter wheat is mostly limited through excess water, insufficient radiation, as well as frost and heat stress. Over the investigated period from 1983 to 2010, few regional trends in climate suitability were identified for the two crops, indicating that grain maize has benefitted slightly from increasing growth temperatures with recent warming (0.5 °C/decade), while winter wheat suitability decreased slightly due to suboptimal radiation/temperature ratios with warming. Despite only small trends in climate suitabilities, which are restricted to particular regions, future climatic changes could lead to more pronounced shifts. The tendencies of climate limitations identified in this study are mostly consistent with findings from other studies, and it can thus be anticipated that maize may continue to benefit from increasing temperatures on the short term, but may also be increasingly limited by water scarcity as summer precipitation decreases. For winter wheat, the relevance of heat stress is likely to increase with increasing temperatures. These results may help to support short-term adaptation planning. However, more detailed analyses of climate projections will be necessary to investigate "critical transitions" and provide more specific information to support long-term climate change adaptation planning (e.g. for irrigation and breeding programmes).

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Introduction

Agriculture plays an important role in Switzerland, a country with a complex topography and diverse microclimatic conditions. As the country is very densely populated, and space for construction competes with land for agriculture, the pressure on land is high, and thus, land use planning is essential to make best possible use of the limited resource (FAO 1993). The aim of the Federal agricultural policy is to achieve maximum crop yield with minimum inputs in order to maintain high agricultural productivity, while minimizing environmental impacts (see Swiss constitution, Art. 104). This requires that agricultural management is best adapted to specific site conditions including climate, topography, and soil. While topography and soil remain largely constant over time, climatic conditions vary not only in space, but also from year to year; climate variability in time is a major driver of inter-annual yield fluctuations (Lobell and Field 2007). To cope with possible shifts in land suitability due to future changes in climatic conditions, land allocation to the production of specific crops and crop management need to be adapted to account for spatial shifts in climatic limitations. However, preparing such adaptation requires understanding not only of how climatic conditions differ regionally, but also how climatic suitability and climatic limitations change over time (Dong et al. 2009; Peltonen-Sainio et al. 2010). Jeanneret and Vautier (1977) assessed average climate suitability in Switzerland based on available information up to 1976. Their evaluation included separate maps for grassland, potato, grain maize, winter crops, catch crops and specialty crops (e.g. fruit trees). For potato, grassland, and winter crops, their evaluation was based on interpolated climate data; for grain maize on expert judgement and literature data (e.g. Primault 1972) and for specialty crops and catch crops, it was based on data from Schreiber et al. (1977). Changes in climate suitabilities over time were not assessed, and since the approach is not fully reproducible, it cannot be applied for re-evaluation and trend analysis.

Since 1961, considerable trends in mean temperature from March to August of about 0.5 °C/10 years (relative to the mean for 1961–1990) have been observed in Switzerland (Ceppi et al. 2012; MeteoSwiss 2012b). These recent changes may already have caused shifts in suitability patterns for crops that need to be explored. Also, for any further consideration of future climate change impacts on crops, relationships between climate and crop productivity need to be analysed based on observed data (Lobell et al. 2011). The goal of this study was therefore to provide a spatially explicit evaluation of crop-specific climate suitability and climate limitations, and to explore whether recent temperature trends had significant influences on climate suitabilities. The focus was on grain maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.), two major crops in Switzerland with considerable differences in their growth cycles and thus potentially different responses to changes in climatic variables. The knowledge- and data-based approach recently developed for maize by Holzkämper et al. (2013) was adopted for winter wheat, and both models were used (1) to analyse the distribution and trends in climate suitability for these two crops and (2) to identify limitation by individual climatic factors.

Data and methods

Crop-specific climate suitability was calculated on an annual basis from agro-climatic indices derived for dynamically estimated phenological phases. The phenophase-specific climate indices are called 'factors'. Factor suitability functions were specified to relate factor values to factor suitability scores ranging from 0 to 1. Following the procedure described in Holzkämper et al. (2013), factor suitability functions were initially defined based on scientific literature and expert knowledge, and in a second step, refined based on observed crop yields from the Farm Accountancy Data Network of Switzerland (FAT 2003).

Data

Gridded daily data for minimum, maximum and average temperature (°C), precipitation (mm) and surface incoming shortwave radiation (MJ/m^2) at a spatial resolution of 0.02° latitude and longitude were used as the basis for this spatio-temporal analysis of climate suitabilities and limitations. Interpolated temperature and precipitation data for the period 1983–2010 were provided by MeteoSwiss (Frei and Schär 1998; Frei et al. 2006; MeteoSwiss 2012a). Radiation data from 2004 to 2010 derived from satellite data were also available from MeteoSwiss (Stöckli 2013), and for earlier years from 1983 to 2003, data from the satellite application facility on climate monitoring (CM SAF) were used (Posselt et al. 2012). As these data on surface incoming shortwave radiation were only available with a resolution of 0.03° latitude and longitude, they were resampled using nearest neighbour interpolation to match the resolution of the other datasets. A comparison of data from the two sources for the overlapping period (2004–2005) showed that differences were small in the lowland regions where climate suitability was estimated (i.e. average deviations between 0.35 and 1.12 MJ/m^2 per day, depending on period of year).

Crop phenological data for winter wheat were available from official registration variety field trials (Agroscope, unpublished data). The dataset contained information over the years 2009–2011 for 8 different locations and 43 varieties with relatively minor variation in phenological development (less than 10 days). Climate data from the closest meteorological stations were matched with available phenological data to establish a dataset that could be used to adjust and test the phenology models.

For the data-based refinement of factor suitability functions within the climate suitability evaluation for winter wheat crop yield observations from the farm accountancy data network of Switzerland were used (FAT 2003). Climate data from automated meteorological stations were matched with average annual winter wheat yields within a 15-km radius around the station coordinates. Observed winter wheat yields and climate data for all required parameters were available for 18 stations and between 11 and 27 years, resulting in a dataset with 383 records.

Implementation of climate suitability evaluation approach for winter wheat and grain maize

Phenology

Sowing dates and phenological development were estimated dynamically for both crops. For grain maize, the sowing window extending from April 15 to May 31 with sowing taking place once the average temperature over the last 10 days exceeds 12 °C, assuming that soil temperature under these conditions is adequate for sowing (Holzkämper et al. 2013). For winter wheat, sowing date was estimated dynamically based on temperature and in addition also based on precipitation during 6 days in a pre-defined sowing window (October 7–November 7). For sowing to take place, average air temperature over the last 6 days has to be below 12 °C (value derived from field trial data) and precipitation during the 5 previous days has to be <20, <16, <12, <8 and <4 mm, respectively. With this expert-based modification of the purely temperature-based estimation, a final root mean square error of 6 was achieved in comparison with observed sowing dates derived from field trial data ($n = 258$ including sites with <10 km distance to closest climate station).

While for grain maize the phenology model proposed by Holzkämper et al. (2013; see Table 1) could be used, estimates of growing degree days (GDDs) for the winter wheat growth cycle were derived from available field trial data by calculating GDDs between planting and harvest, assuming a base temperature of 0 °C. The median GDD sum derived from field trial data (= 2,440 GDD; $n = 125$) was taken as the requirement for reaching maturity. Because data for intermediate phenological stages were not available, intermediate GDD thresholds were adjusted for Swiss conditions by scaling GDD requirements defined by Lang and Müller (1999; i.e. E = 150 GDD; GS1 = 500 GDD; GS2 = 1,125 GDD; GS3 = 2,200 GDD) to the target value of 2,440 GDD. The resulting GDD requirements are shown in Table 1. Latest harvest date was set to August 31. A comparison of documented and simulated harvest dates showed a root mean square error of 5.72 ($n = 344$ including sites with <10 km distance to closest climate station). The plausibility of intermediate phenology dates was checked for the station of Changins located to the west of Lake Geneva; average dates estimated for this site were November 7 for 3-leaf stage, February 25 for double ridge and May, 17 for anthesis. These estimates were generally consistent with expectations of field experts.

Table 1 GDD requirements for grain maize (base temperature 6 °C) and winter wheat (base temperature 0 °C); latest harvest date November 15 (grain maize) and August 31 (winter wheat)

Grain maize		Winter wheat	
GDD requirement (°C *d*)	Phase description	GDD requirement (°C *d*)	Phase description
100	Planting to emergence (Em)	166	Planting to 3-leaf stage (the optimum stage for overwintering; Gate 1995) (E)
800	Emergence to begin flowering (Flo)	555	3-leaf stage to double ridge (vegetative growth; GS1)
1,100	Flowering to begin grain filling (Fil)	1,248	Double ridge to anthesis (reproductive growth; GS2)
1,600	Begin grain filling to harvest (Mat)	2,440	Anthesis to harvest (grain filling; GS3)

Factor suitability

For both crops, six climate indices were used to represent major factor limitations in each of the four phenological phases (Table 2). The bounds for phase-specific factor suitability functions were defined on the basis of literature data and expert knowledge. For phases where specific limitations are known to be more relevant, the bounds were defined more restrictively. For winter wheat, for example, limited water availability and heat stress are known to be most critical during GS2 (FAO 2002), which is considered in the knowledge-based bounds (see "Appendix").

'Overall' climate suitability S was derived as a weighted linear combination of the four phase-specific minimum suitabilities, assuming that each factor suitability s_f can limit growth within each phase p, but lower suitability in one phase can be compensated for by higher suitability in another phase:

$$S = w_1 * \min(s_{1,1}, \ldots, s_{1,f}) + \cdots + w_p * \min(s_{p,1}, \ldots, s_{p,f}) \quad (1)$$

For this implementation, equal weights for all phases as in Holzkämper et al. (2013) were applied (w1, w2, w3, w4 = 0.25) assuming that climate limitations in each phase contribute equally to overall climate suitability. Where temperatures were too low for reaching the maturation phase, suitability was not evaluated due to assumed harvest failure.

Model fits

Within pre-defined bounds, the suitability functions were optimized to achieve the best fit between suitability estimates and scaled observed yields, as described in

Table 2 Factor limitations for grain maize and winter wheat

Limitation	Grain maize suitability factors	Winter wheat suitability factors	Description
Frost stress	TIMNb0	TIMNb0	Average daily minimum temperature below 0 °C in absolute values (°C)
Temperature determining plant growth	avgTemp	avgTemp	Average daily mean temperature (°C)
Heat stress	TMAXa35	TMAXa25	Average daily maximum temperatures exceeding 25 °C for winter wheat (Acevedo et al. 2002) and 35 °C for grain maize
Water stress (water limitation or excess water)	avgWA	avgWA	Average daily water availability [= precipitation—reference evapotranspiration calculated according to Priestley and Taylor (1972)] (mm)
Radiation limitation	avgRad	PTQ	Average daily solar radiation (MJ/m^2) for grain maize and the photo-thermal quotient calculated as average daily solar radiation (MJ/m^2) divided by average daily mean temperature [°C] for winter wheat
Phenological development	Len	Len	Length of the phenological period as described in Table 1 (*d*)

For winter wheat, PTQ replaces avgRad to improve the model fit based on the assumption that the interaction between radiation and temperature effects is highly relevant for wheat yields as documented in various publications (e.g. Fischer 1985; Nix 1976; Nalley et al. 2009)

Holzkämper et al. (2013). For this purpose, the climate-yield dataset introduced in the "Data" section was split up into a calibration and a validation dataset. Due to the limited size of the overall dataset, only 25 % of all data were spared for validation. The calibration procedure was repeated 50 times, and results were averaged to yield the final functions used in this study. Satisfactory fits could be achieved based on the values of the Willmott-index of agreement *d* (Willmott 1981): calibration for winter wheat achieved a mean *d* of 0.73 with a standard deviation of 0.0014 amongst the 50 calibration runs; mean *d* achieved with the validation dataset was 0.68 (±0.007 SD). In comparison, the average agreement achieved for grain maize in Holzkämper et al. (2013) was $d = 0.74$ (±0.002 SD) for calibration and $d = 0.81$ (±0.002 SD) for validation. Factor suitability functions derived for grain maize are documented in Holzkämper et al. (2013). Factor suitability functions estimated for winter wheat are shown in "Appendix".

Model application

Mean suitability maps and maps showing the average of strongest limitations for all factors were derived for the periods of available data (1983–2010 for grain maize; 1984–2010 for winter wheat where the first year of the time series had to serve as a sowing year only). Trend maps were derived showing significant time trends in factor suitabilities and in overall suitability estimates. To evaluate these trends, the nonparametric Mann–Kendall test was used, which indicates the direction and significance of a trend for equally spaced data (Mann 1945). All spatial calculations were performed using Python (using the netCDF4 package). Statistical analyses were done in R (R Development Core Team 2010), and ArcGIS 10 was used for the visualization of spatial outputs.

Results

Pattern of climate suitability and limiting factors: grain maize

The distribution of mean climate suitability for grain maize for the period 1983–2010 is shown in Fig. 1. The regions with the highest climate suitability index are distributed at lower altitudes across the central Plateau, the Rhone valley (VS), the Rhine valley in the Eastern part (GR, SG), and the Ticino (TI) in the South. Climate suitability for grain maize generally decreased with increasing altitude.

The distribution of mean limitations by individual factors is shown in Fig. 2. Radiation limitation was generally low in the lowlands and increased towards higher altitudes. Limitation by water availability occurred mostly in the Western part of the Plateau, in the Southwest (GE), and in the Rhone valley (VS), whereas Ticino (TI) and higher altitudes showed moderate limitation due to excess water. Climate suitability at higher altitudes was strongly limited by frost. Similarly, limitation due to average temperature and extended growing period length were high at higher altitudes where temperatures are suboptimal for growth and prevent maturation. Limitation caused by heat was generally low, with the highest values around 0.1 in the North and in the Southwest.

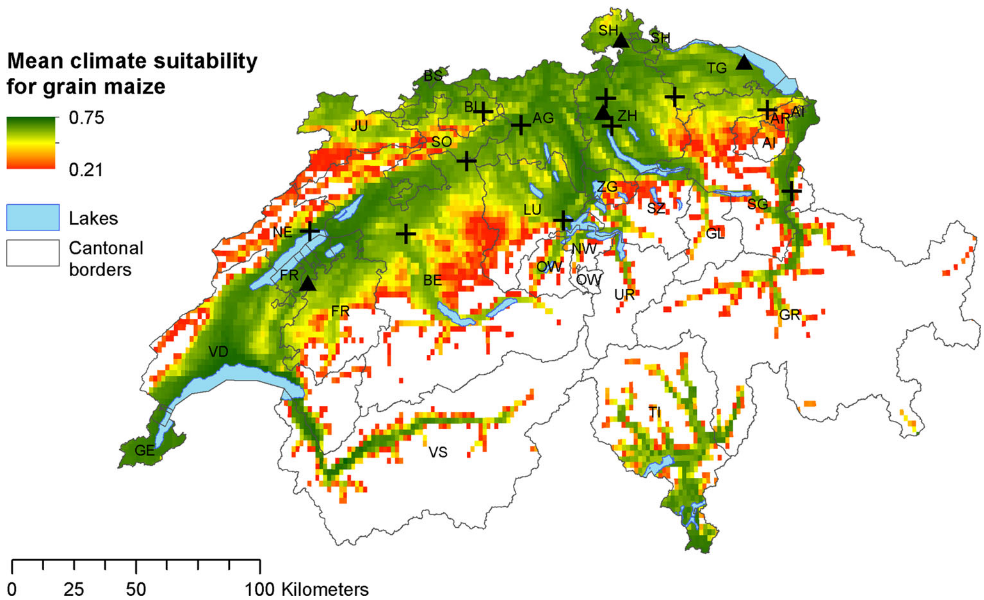

Fig. 1 Average climate suitability for grain maize (1983–2010; labels signify cantons, *crosses* indicate locations of automatic climate stations used for calibration, *triangles* indicate locations of automatic climate stations used for validation)

The importance of individual factors during each phenological phase was further analysed spatially. The results revealed that from planting to emergence (Em), suboptimal average temperature was the most frequent limitation with the widest distribution. In some regions such as the Rhine valley in the East and in the South (TI), radiation was also limiting, and in the South (TI), few scattered areas were most frequently limited by excess water. During vegetative growth from emergence to beginning of flowering (Flo), the most frequent limitation with the widest distribution, especially in the North, was by radiation. Limiting water availability was the most frequent limitation in the Rhone valleys (VS) and in the South-Western part (GE, VD, FR), and excess water was the most frequent limitation at higher altitudes in the South (TI). Insufficient period length due to the temperature-induced acceleration of development was the most frequent limitation in the lowland regions in TI. In contrast, at higher altitudes in the North, period length was generally too long. Few areas on the Central Plateau were also most frequently limited by suboptimum temperature during this phase. From flowering to beginning of grain filling (Fil), limited water availability was the dominating limitation across almost the entire area considered, whereas at higher altitudes towards the Alps and Jura mountains, radiation and suboptimum average temperature were the most frequent limitations. During maturation (Mat), radiation and average temperature were the most frequent limitations with the widest distributions—radiation mostly in the Northern parts. In the South (TI), excess water was the dominating limitation besides suboptimal period length in few locations.

Frost and heat limitations did not occur as most frequent limitations during any of the four growth phases and played a minor role in determining overall grain maize climate suitability.

Pattern of climate suitability and limiting factors: winter wheat

Compared with the situation for grain maize, areas of highest climate suitability for winter wheat estimated over the period 1984–2010 were more widely distributed in the Pre-Alps and in the valleys of Rhone (VS) and Rhine (GR and SG; Fig. 3). Climate suitability was moderate in the South (TI), and in general, decreased with altitude. Radiation deficits were most limiting in the Northern, in the valleys of TI and VS and in the Eastern Rhine valley (SG; Fig. 4). The strongest water stress limitation occurred in the valleys of Rhone (VS) and Rhine (GR), and to a lesser extent in the North and Southwest, whereas in Southern parts (TI), climate suitability was mostly limited by excess water, thus confirming the lower tolerance to excess water in wheat as compared to maize (Ahmed et al. 2013). Limitation due to excess water also increased towards higher altitudes. Like with grain maize, the decrease in climate suitability with altitude was linked to limitations by frost and growing period length, suboptimal average temperature, and wetness. Finally, the heat stress limitation was generally higher for winter wheat than for grain maize, but low in comparison to other limitations. Regions affected by heat stress were evenly distributed in all areas that are climatically suitable for winter wheat, mostly on the Central Plateau (ZH, AG, BE, FR, VD, GE), in the South (TI) and in the Rhone valley (VS).

The analysis of the most frequent limitations over the 27-year period revealed that from planting to 3-leaf stage (E) and during vegetative growth (GS1), excess water was the most frequent limitation with the widest distribution. In GS1, some areas at higher altitudes towards the Alps were most frequently limited by frost. During reproductive growth (GS2), sub-optimal PTQ was the most frequent limitation, and at higher altitudes, it was suboptimum average temperatures.

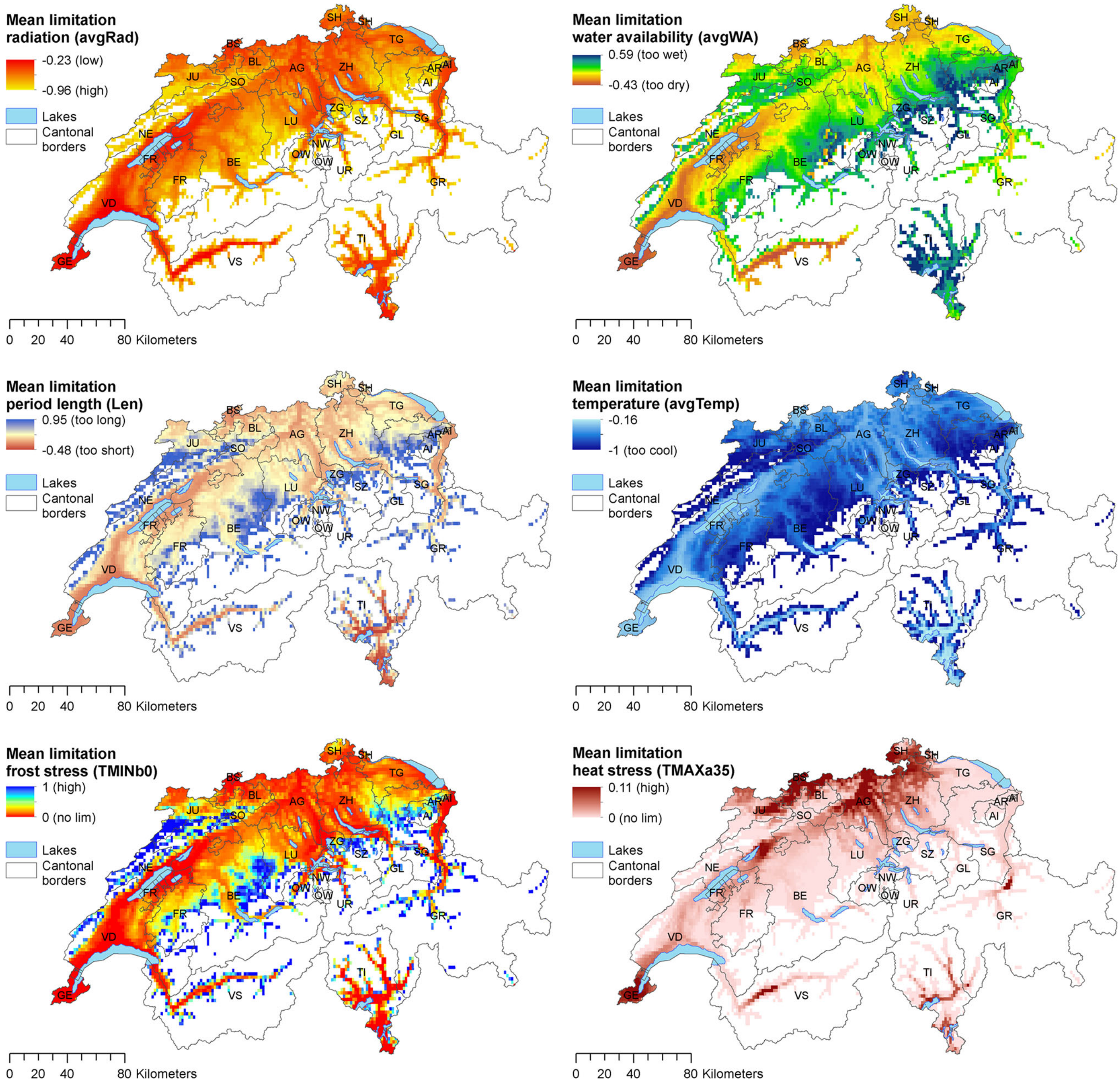

Fig. 2 Average of annual strongest suitability limitations to grain maize climate suitability for each factor (labels signify cantons)

Few areas located mostly in inner-alpine valleys such as the Rhone valley (VS) and valleys of Grisons (GR) were most frequently limited by water scarcity during GS1 and GS2. During grain filling (GS3), suitability was most frequently limited by heat stress and excess water, and in few Eastern regions by insufficient PTQ. Towards higher altitudes, insufficient period length became most limiting.

Trends in suitability limitations

Trend analysis revealed areas with significant positive or negative trends (p values of Mann–Kendall trend test <0.05) in climate suitability. Differences for maize were generally small and mostly positive (Fig. 5a). Strongest positive differences were found on the Central Plateau and in Eastern parts of the country. Few small negative changes were found South of the Alps (TI). For winter wheat, negative trends occurred in the lowland areas (LU, BE, FR and VD) and in the Northwest (JU and BS/BL; Fig. 5b). Some positive trends were observed in single raster cells, mostly at higher altitudes along the Alps.

In Table 3, correlations between decadal changes in mean climate suitability and changes in mean phase-specific factor suitability between the 1983 and 2010 are

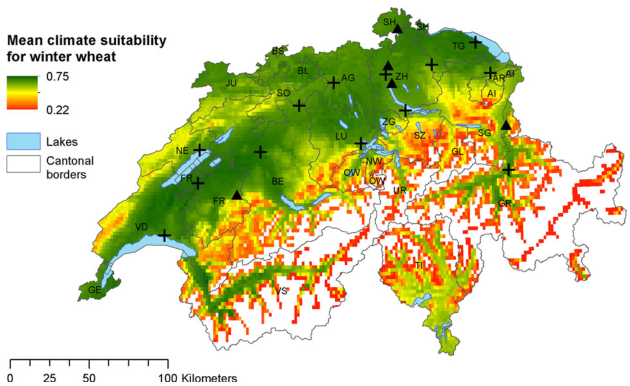

Fig. 3 Average climate suitability for winter wheat (1984–2010; labels signify cantons, *crosses* indicate locations of automatic climate stations used for calibration, *triangles* indicate locations of automatic climate stations used for validation)

summarized for grain maize. Differences in estimated climate suitability were most strongly correlated with temperature-related factor suitabilities (i.e. period length and average temperature). Trends in factor suitability for period length from emergence to begin of flowering, TMINb0 during maturation, avgTemp from emergence to begin of flowering, and during maturation showed significant positive correlations with trends in climate suitability (p values <0.01). Thus, these factors can be considered as drivers of trends in climate suitability (Table 3).

The spatial distributions of trends in correlated factor suitabilities are shown in Fig. 6. Factor suitability for period length from emergence to begin of flowering showed significant positive trends in the North and Northeast, and negative trends in the South where the only significant negative trends in climate suitability were observed. Factor suitability for average temperature during this phase increased generally, most pronounced in Northern parts and in elevated areas in the valleys of Rhone and Rhine. These changes, in combination with positive trends in factor suitability for avgTemp and TMINb0 during maturation, could explain the increases in overall maize climate suitability.

Correlation analysis for winter wheat revealed that regional trends in climate suitability were best related to trends in period length during the maturation phase (Table 4). Other significant positive correlations were observed with factor suitability for PTQ and avgWA during maturation. Figure 7 shows maps of the respective factor suitability trends. These reveal that significant factor suitability trends for PTQ and avgWA were mostly negative, thus suggesting that increasing waterlogging and decreasing radiation–temperature ratios caused a decrease in overall climate suitability. Factor suitability trends for period length during maturation were mostly positive. The strong positive correlation of these trends with trends in overall climate suitability suggested that the few occasions with increased overall climate suitability could be attributed to increasing temperatures, allowing maturation at progressively higher altitudes (Fig. 7).

Discussion

Evaluation approach

The approach used in this study enables the spatio-temporal analysis of patterns of crop-specific climate suitability and climatic limitations for the cultivation of winter wheat and grain maize. As the results of an independent validation based on yield data show, crop-specific climate suitability indices can be considered as estimates of yield potentials with good confidence. The conceptual structure of the modelling approach allows for separating different climate impacts so that individual limiting factors can be identified. By replacing avgRad with PTQ for winter wheat, a relevant compensatory effect between radiation and temperature during flowering and grain filling was introduced that could not be captured with the minimum approach if both effects were integrated separately. A significantly better model fit for the winter wheat suitability evaluation was achieved with PTQ than with avgRad ($d = 0.73$ as opposed to $d = 0.62$ with avgRad; results not shown). As described in previous studies, high solar radiation increases photosynthesis and can thus affect grain yields, while high temperatures around the same period have negative effects on yields through shortening the duration of spike growth (Fischer 1985; Nalley et al. 2009). A similar effect for grain maize has not been documented in the literature. Here, a stronger correlation of grain yields with average radiation was found than with PTQ (Pearsons's $r = 0.45$*** with avgRad during maturation, Pearsons's $r = 0.4$*** with PTQ during maturation), confirming that avgRad is a more suitable factor for grain maize suitability evaluation.

It must be noted that in the present implementation, our approach does not consider that regionally adapted crop varieties may be cultivated in different regions. It rather quantifies climatic yield potentials for an "average variety", which represents the average characteristics of the varieties grown during the investigated period of time in those regions from which data for calibration were used (see point locations in Figs. 1 and 3). Therefore, specific limitations by climatic factors could be overcome by regionally adapted varieties. For example, it seems likely that the frequent limitation due to accelerated crop development (i.e. insufficient period length) identified south of the Alps (TI) is in practice outweighed by the cultivation of varieties with higher temperature requirements in this

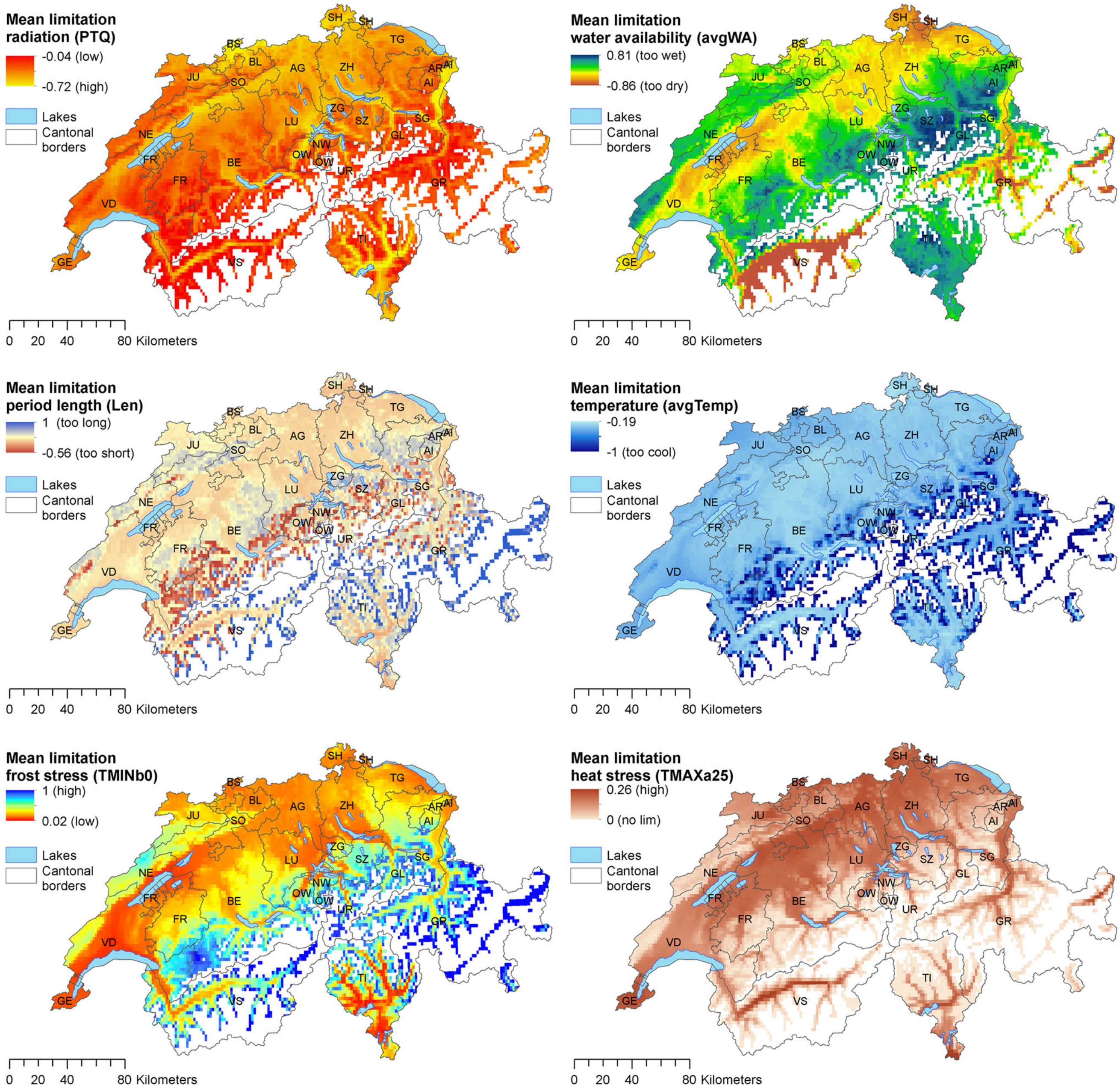

Fig. 4 Average of annual strongest suitability limitations to winter wheat climate suitability for each factor (labels signify cantons)

region (Hiltbrunner et al. 2013). With continuous improvements in crop breeding (Mackay et al. 2011), varieties selected for cultivation have most likely shifted towards high-yielding earlier-maturing varieties to increase the flexibility in rotation planning and extend cultivation zones towards cooler regions in higher altitudes. This could have reduced the practical limitation by overlong "period length" due to delayed phenological development shown in Figs. 2 and 4.

In general, the concept of effective temperature sum for simulating phenology as it was applied in this study is justified at the large scale (Siebert and Ewert 2012). However, pheno-model improvements for example by integrating effects of photoperiod, which can be very important for winter crops, could be considered in future studies.

Sowing dates can differ between locations and years not only depending on climatic conditions (i.e. temperature and soil water content), but also depending on agronomic factors (e.g. crop rotations). Thus, in reality, climate dependencies could deviate slightly from those estimated in this study as phenological phases could be shifted. However,

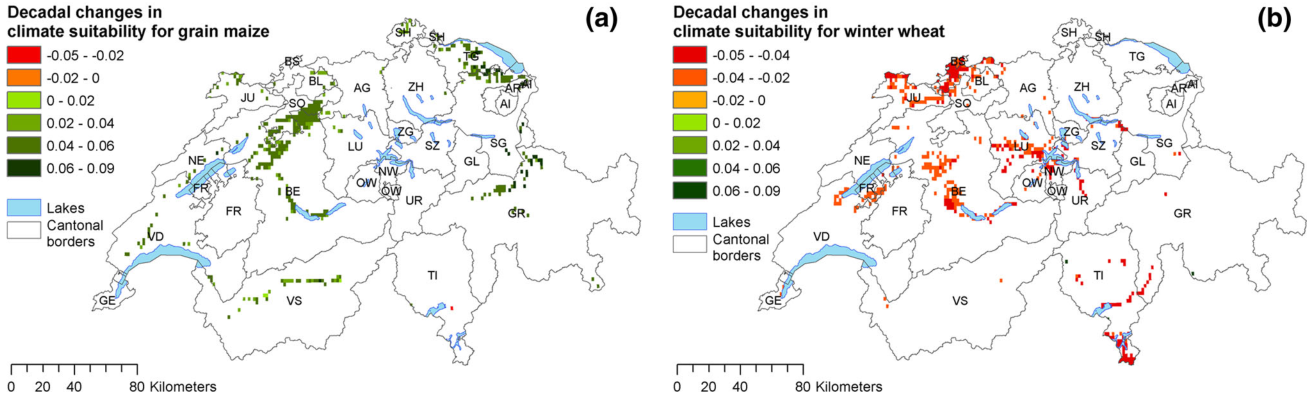

Fig. 5 Decadal changes in grain maize **a** and winter wheat **b** climate suitability in areas with significant trends (p value <0.05; labels signify cantons)

Table 3 Correlations between decadal changes in mean grain maize suitability as shown in Fig. 5a and decadal changes in mean phase-specific factor suitabilities between the same periods; stars indicate the significance levels: *** p value <0.001, ** p value <0.01, * p value <0.05 [values in brackets indicate number of overlapping cells with significant trends ($p < 0.05$) in climate suitability and factor suitability]

	TMINb0	avgTemp	TMAXa35	avgRad	avgWA	Len
Em				0.25* [65]		
Flo		0.33*** [157]				0.71*** [98]
Fil		0.14 [21]				0.11 [33]
Mat	0.18** [338]	0.16** [414]		−0.11* [349]	−0.13 [32]	0.17* [165]

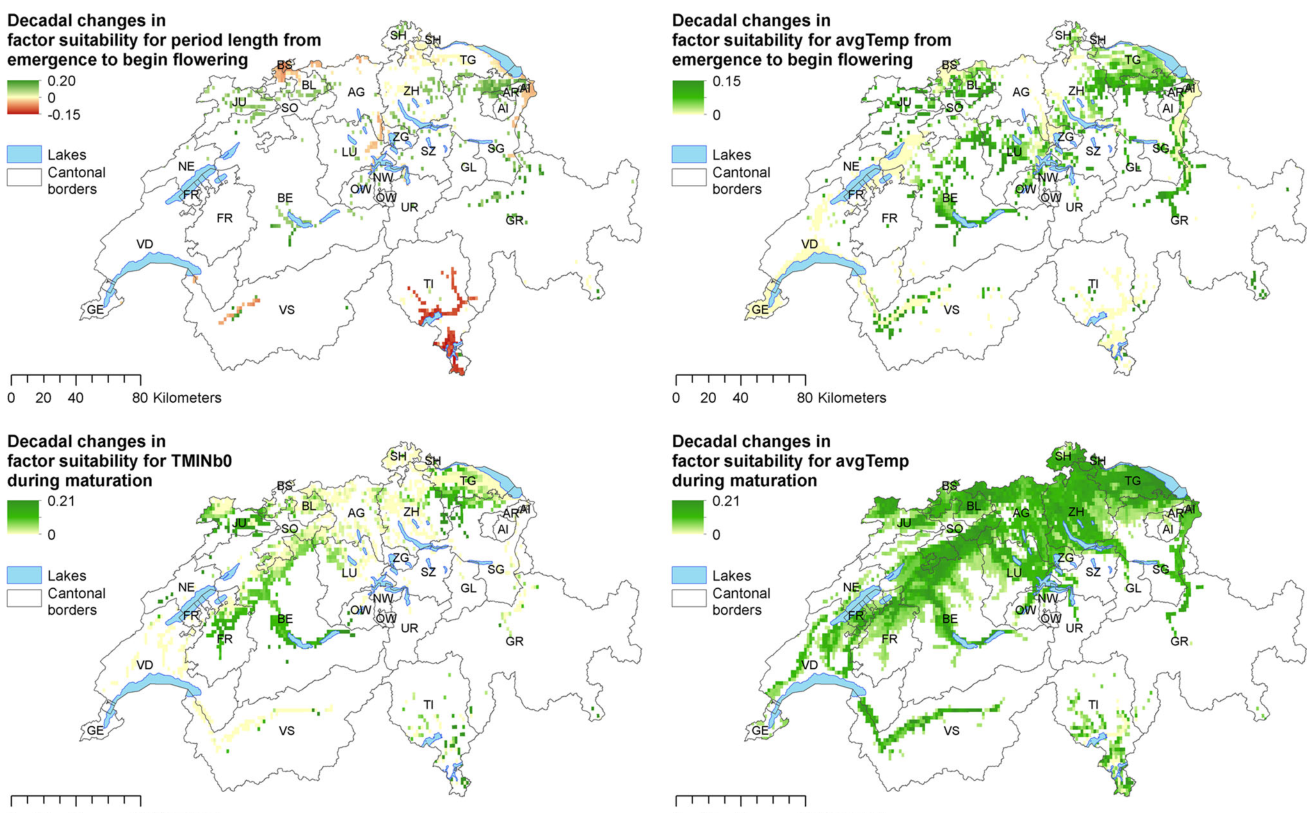

Fig. 6 Decadal changes in factor suitabilities for grain maize that show significant positive correlations with climate suitability (shown in areas where trends are significant at p value <0.05; labels signify cantons)

Table 4 Correlations between decadal changes in mean winter wheat as shown in Fig. 5b and decadal changes in mean phase-specific factor suitabilities between the same periods; stars indicate the significance levels: *** p value <0.001, ** p value <0.01, * p value <0.05 [values in brackets indicate number of overlapping cells with significant trends ($p < 0.05$) in climate suitability and factor suitability]

	TMINb0	avgTemp	TMAXa25	PTQ	avgWA	Len
E					−0.59*** [35]	
GS1	−0.04 [47]					
GS2	0.00 [16]		−0.3 [21]	0.28 [39]		
GS3			0.25 [43]	0.34*** [503]	0.28** [96]	0.92*** [94]

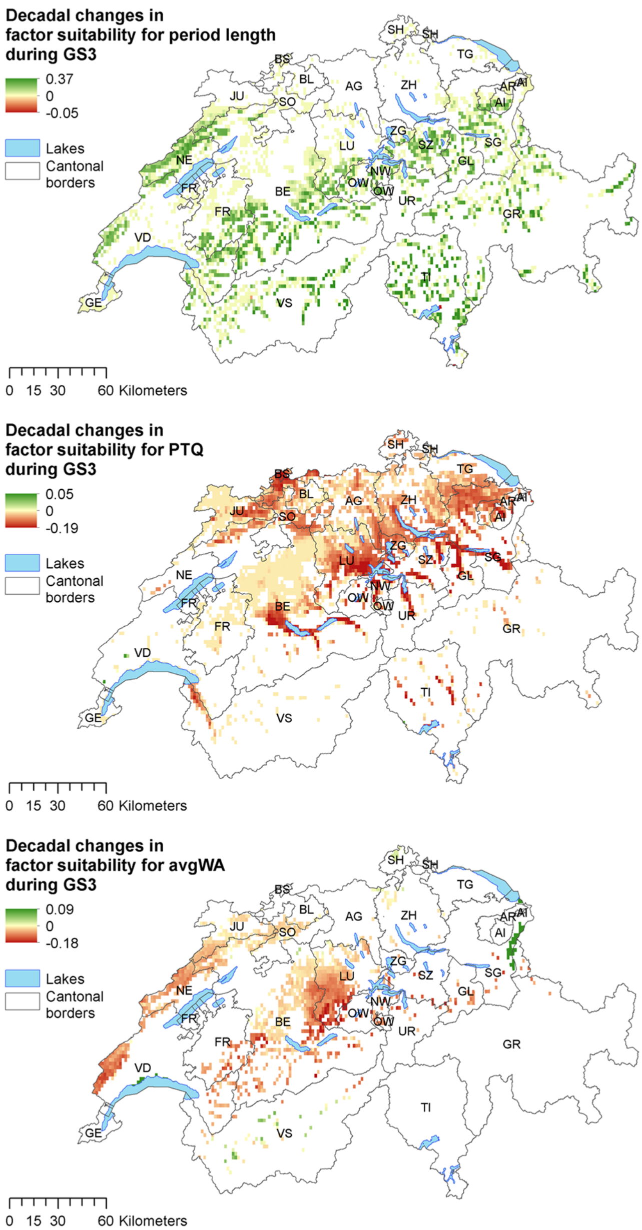

Fig. 7 Decadal changes in factor suitabilities for winter wheat that show significant positive correlations with climate suitability (shown in areas where trends are significant at p value <0.05; labels signify cantons)

such small-scale differences could not be accounted for in this study, as the aim was to identify spatial and temporal variation of crop-specific climate suitability and limitations at the larger scale. Effects of local soil conditions on the water balance and thus on water availability for plants were also not considered here as the evaluation focused only on climate potentials. Finally, it has to be noted that certain impacts such as snow cover, storms or hail on crop production cannot be estimated with this approach.

Mean climate suitability and limiting factors

The application of the method to Switzerland reveals similar spatial patterns of factor limitations for both crops. At higher elevation, temperature, period length and frost stress restrict climate suitability. However, as grain maize requires higher temperatures, climate suitability is more strongly restricted by these factors, while the climate suitability for winter wheat expands into higher and cooler regions. Differences in climatic limitations can be explained by the fact that the two crops differ in their growing cycle and in sensitivities to climatic impacts/factor definition.

While most limitation maps could not be compared with results of previous studies, identified patterns of precipitation limitation are well in line with the spatial distribution of potential irrigation requirements obtained by Fuhrer (2011) using a hydrological model. Limitation by water stress for both crops is most severe on the Central Plateau (TG, ZH, AG, SH, BE, FR, VD) and in inner-alpine valleys (VS, GR) suffering from a rain-shadow effect. Differences in regional distributions of water limitations for both crops can also be identified in the Southwest around Lake Geneva (GE, VD) where average water stress limitation is more severe for grain maize than for winter wheat, which can be explained by temporal differences in the spatial distribution of water deficits and differences in phenological development between crops. The flowering period, during which both crops are most sensitive to water stress, occurs earlier for winter wheat and when water deficits in this region are on average less severe than during the critical period for maize. This highlights the relevance of considering the timing of crop phenology and its interactions with crop-specific requirements in climate-related impact studies, in agreement with Tao et al. (2012). Thus, the present study goes a step beyond similar studies such as the one by Jayathilaka et al. (2012), who investigated spatial shifts in crop suitability for tea, rubber and coconut in Sri Lanka using a multi-criteria evaluation approach based on annually aggregated climate data.

Trends in climate suitability and limiting factors

Over the years considered in this study (1983–2010), few regional trends in climate suitability can be identified at relatively low significance level of $p < 0.05$. This suggests that, in general, climate suitability for both crops has remained fairly stable over the last decades with only weak trends towards decreasing suitability for winter wheat and increased suitability for grain maize.

According to our analysis, grain maize suitability tends to benefit from the increase in mean temperature observed over this period, which is in line with Olesen et al. (2011) who report positive trends in grain maize yields, but also state that particularly in Southern Europe, maize yield decreases are to be expected with climate change. For future climate conditions, Olesen et al. (2007) estimated an expansion of thermal suitability for grain maize cultivation into Northern regions and higher elevations in Europe by 30–50 % across all SRES emissions scenarios. However, contrary to the findings of Hawkins et al. (2013), who investigated the influence of heat stress on French maize yields from the 1960s to the 2030s, we could not identify an influence of increasing heat stress on grain maize suitability. This lack of significant trends in heat stress could be due to the shorter time period investigated here. It could also be explained by the advancement of plant development with warming that was not considered in the study of Hawkins et al., but which influences the heat stress indices estimated here. Further possible reasons for the different findings could be that a lower heat threshold of 32 °C was used by Hawkins et al., and the fact that irrigation, which was believed to have influenced the relative importance of heat stress variability in their study, was not considered here.

For winter wheat, climate suitability has mostly decreased due to decreasing PTQ with increasing temperatures on the one hand and increases in excess water limitation during maturation on the other hand. Thereby, the increase in excess water limitation is restricted to areas that tend to be limited by excess water in general and where summer precipitation increased over the last decades (MeteoSwiss 2013). Since solar radiation data was only available from two different data sources (see "Implementation of climate suitability evaluation approach for winter wheat and grain maize" section), the contribution of PTQ to the identified trends has to be interpreted with caution. Negative trends in average seasonal radiation found in the gridded data could not be confirmed based on observed weather station data (results not shown). This suggests that the decrease in PTQ and, consequently, the decrease in winter wheat climate suitability could be overestimated here. Few areas with positive trends in climate suitability at higher elevations suggest that climate suitability has shifted slightly towards higher elevation where the probability of reaching maturity increases as temperatures increase, in line with findings of Olesen et al. (2007, 2011). Our finding that heat stress during maturation is frequently limiting for winter wheat points in the same direction as results of a simulation study by Semenov and Shewry (2011) who found that based on climate change projections heat stress and not water stress will increase the vulnerability of wheat in Europe. Also, Brisson et al. (2010) found that from 1990 onwards, increasing summer temperatures have deteriorated conditions for winter wheat in France due to heat stress during grain filling. Likewise, Olesen et al. (2011) state that risk of heat stress is likely to increase with climate change. For the period investigated in this study, we could not identify such trends, even though significant positive trends in summer days have been observed (MeteoSwiss 2012b). This could be explained by the fact that the temperature-related acceleration of the phenological development shifts sensitive phases away from the periods of most intense heat and water stress, an aspect that was not considered in the study by Olesen et al. (2011). As temperature increases, phenological development is accelerated and maturity is reached earlier. This can help to prevent water stress as sensitive periods shift towards the time of year with less intense water scarcity, which indicates some potential of phenological adaptations to climatic changes. Also, Ludwig and Asseng (2010) found in their simulation study with APSIM-Nwheat that in drier climates earlier flowering varieties increase potential yield while in warming climates later varieties increase yield. However, given that the evaluation approach does not consider spatial or temporal variation in crop varieties, it may be debatable whether or not such effects would occur in reality, as farmers would choose varieties according to local conditions and the choice would be adapted continuously according to changing conditions (Liu et al. 2010; Sacks and Kucharik 2011).

The observation that changes in climate suitability for both winter wheat and grain maize are small might be unexpected, given that during the last 30 years highly significant positive trends in spring and summer temperatures of 0.5 °C per decade occurred in Switzerland (MeteoSwiss

2012b). Only marginal trends towards drier summertime conditions have been observed during the period analysed here, and hence, a change in limitation by water availability was not detectable. Moreover, because factor suitabilities are derived for dynamically estimated phases, the link between trends in initial climate variables and trends in factor suitabilities is not always evident. Trends in climate suitabilities may be damped by counteracting effects of increasing temperatures improving conditions for growth and acceleration of plant development, shifting phenological stages into periods when growth conditions are less suitable or reduce yield due to shortened time for biomass accumulation (Fischer and Maurer 1976). These effects of the same driver are represented through the two indices "average temperature" and "period length". When comparing the distributions of both average limitations for maize (Fig. 2), it becomes evident that the limitation by "average temperature" is low in the warmer lowland areas where the limitation by "period length" is high. Besides such counteracting effects of different factor suitabilities, another possible reason for the relatively small sensitivity of climate suitability to trends in climate could lie in the nonlinear shape of most factor suitability functions: factor suitability can be less responsive to changes in a climate index value within a certain range, i.e. the plateau of the optimum function, where crops are resilient to changes in climate variables. However, if critical thresholds are exceeded, even small changes could have strong effects. Such "critical transitions" are difficult to anticipate because the thresholds are uncertain and because of complex interactions and feedbacks in the system (Barnosky et al. 2012). Therefore, extrapolation of the present results to future climates remains difficult and further research into impacts of climate change projections on future crop-specific climate risks is needed to provide specific guidance for long-term adaptation planning (e.g. irrigation planning or prioritizing investments in breeding programmes and variety selection (Chapman et al. 2012)).

Summary and conclusions

The presented analysis of spatio-temporal patterns of climate suitability allows for identifying the distribution of the major limiting factors and of their trends. The results suggest that current climate suitability for grain maize in Switzerland is mostly limited by sub-optimal temperatures, radiation and water stress, while climatic suitability for winter wheat is mostly limited through excess water, frost and heat stress. We found considerable regional differences in suitability and its limitations showing that higher altitudes have limited climatic suitability for both crops due to increasing frost stress, sub-optimum temperatures and related to that, insufficient phenological development. Water stress limitations are generally most severe in the inner-alpine valleys, in Western and North-Western regions. Excess water becomes mostly limiting at higher altitudes and South of the Alps. This limitation is more restrictive for winter wheat than for grain maize.

The identified spatial variability in crop-specific climate limitations suggests that breeding efforts to reduce sensitivities to region-specific abiotic stress factors and to adapt the phenological development to prevailing conditions play an important role in keeping local production risks at a minimum. The results of this study may help to support region-specific variety selection and steer breeding programmes towards a reduction in main climate limitations.

Over the period analysed, observed, significant trends in mean temperature (0.5 °C/decade) had only a small positive effect on the climate suitability for grain maize, and a small negative effect in the case of wheat. The apparent resilience is most likely due to the fact that critical thresholds of limiting factor are rarely exceeded with this trend in temperature. We found that the spatial patterns and trends of limitations and trends in limitations differ substantially between crops due to different crop phenological developments, which highlight the relevance of the timing of sensitive phenological events/phases in connection with crop-specific climate sensitivities.

Despite only small trends in climate suitabilities, which are restricted to particular regions, future climatic changes could lead to more pronounced shifts. The tendencies identified in this study are mostly consistent with findings from other studies, and it can thus be anticipated that maize may continue to benefit from increasing temperatures on the short term, but may also be increasingly limited by water scarcity as summer precipitation decreases. For winter wheat, the relevance of heat stress is likely to increase with increasing temperatures. The results of this study may thus help to support short-term adaptation planning. However, more detailed analyses of climate projections will be necessary to investigate "critical transitions" and provide more specific information to support long-term climate change adaptation planning (e.g. for irrigation and breeding programmes).

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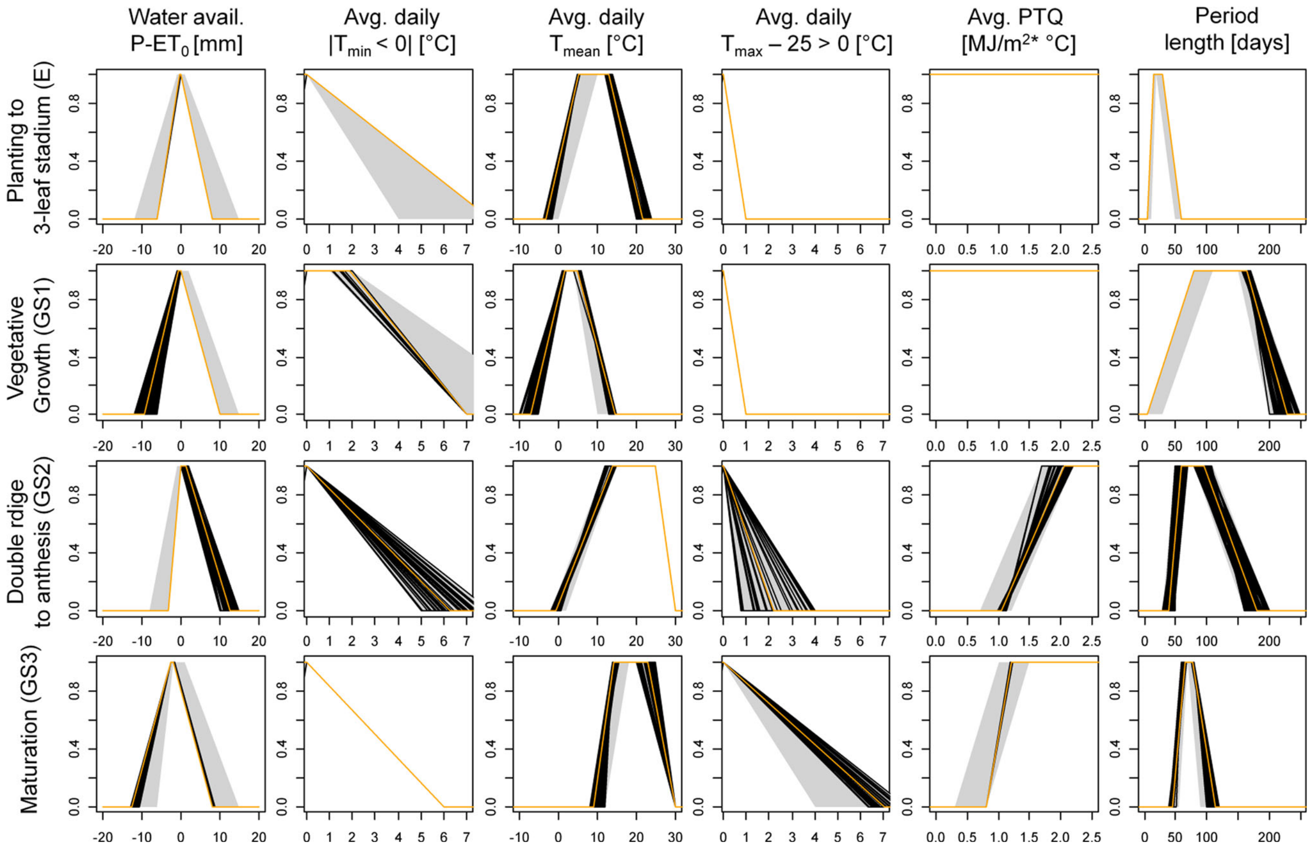

Fig. 8 Factor suitability functions for winter wheat identified in 50 GA runs (*black lines*; *orange lines* show average functions) within the predefined knowledge-based bounds (*grey areas*) (*P* precipitation, ET_0 reference evapotranspiration, T_{min} minimum temperature, T_{max} maximum temperature, *PTQ* photothermal quotient calculated as average daily solar radiation [MJ/m2] divided by average daily mean temperature [°C]) (colour figure online)

Appendix

Factor suitability functions for winter wheat identified in 50 GA runs (black lines; orange lines show average functions) within the pre-defined knowledge-based bounds (grey areas) [P = precipitation, ET_0 = reference evapotranspiration, $T_{\min}$ = minimum temperature, $T_{\max}$ = maximum temperature, PTQ = photothermal quotient calculated as average daily solar radiation (MJ/m^2) divided by average daily mean temperature (°C); Fig. 8].

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