Agroclimatic conditions in Europe under climate change

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Abstract

To date, projections of European crop yields under climate change have been based almost entirely on the outputs of crop-growth models. While this strategy can provide good estimates of the effects of climatic factors, soil conditions and management on crop yield, these models usually do not capture all of the important aspects related to crop management, or the relevant environmental factors. Moreover, crop-simulation studies often have severe limitations with respect to the number of crops covered or the spatial extent. The present study, based on agroclimatic indices, provides a general picture of agroclimatic conditions in western and central Europe (study area lays between 8.5°W–27°E and 37–63.5°N), which allows for a more general assessment of climate-change impacts. The results obtained from the analysis of data from 86 different sites were clustered according to an environmental stratification of Europe. The analysis was carried for the baseline (1971–2000) and future climate conditions (time horizons of 2030, 2050 and with a global temperature increase of 5 °C) based on outputs of three global circulation models. For many environmental zones, there were clear signs of deteriorating agroclimatic condition in terms of increased drought stress and shortening of the active growing season, which in some regions become increasingly squeezed between a cold winter and a hot summer. For most zones the projections show a marked need for adaptive measures to either increase soil water availability or drought resistance of crops. This study concludes that rainfed agriculture is likely to face more climate-related risks, although the analyzed agroclimatic indicators will probably remain at a level that should permit rainfed production. However, results suggests that there is a risk of increasing number of extremely unfavorable years in many climate zones, which might result in higher interannual yield variability and constitute a challenge for proper crop management.

Keywords: agroclimatic extremes, agroclimatic index, climate-change impacts, crop production, environmental zones

Introduction

Climate change is expected to affect both regional and global food production through changes in overall agroclimatic conditions (e.g. Fischer *et al.*, 2005; Solomon *et al.*, 2007). The observed warming trend throughout Europe (+ 0.90 °C from 1901 to 2005) is well-established (Alcamo *et al.*, 2007); however, precipitation trends are more spatially variable, wherein mean winter precipitation has increased in most of the Atlantic and northern Europe (Klein Tank *et al.*, 2002) but has changed little in Central Europe (e.g. Brázdil *et al.*, 2009). Furthermore, trends are negative in the eastern Mediterranean, and no significant change has been observed in the west (Norrant & Douguédroit, 2006). According to Alcamo *et al.* (2007), the effects of climate change and increased atmospheric CO_2 levels by 2050 are expected to lead to small increases in European crop productivity, but temperature increases greater than approximately 2 °C would likely lead to declines in the yields of many crops (Easterling *et al.*, 2007). Several climate projections for 2050 exceed this 2 °C threshold (Giorgi & Lionello, 2008).

Although different studies have resulted in different projections, all agree on a consistent spatial distribution of the effects, leading to the need for the regionalization of adaptation policy (Ciscar *et al.*, 2009; COM, 2009). The projected increase in extreme weather events (e.g. periods of high temperature and droughts) over at least some parts of Europe is predicted to increase yield variability (Jones *et al.*, 2003; Porter & Semenov, 2005; Lavalle *et al.*, 2009; Quiroga & Iglesias, 2009; Iglesias *et al.*, 2010). Technological development (e.g. new crop varieties and improved cropping practices) could ameliorate the effects of climate change (Ewert *et al.*, 2005; Peltonen-Sainio *et al.*, 2009a). However, there is evidence of a slowing rate of yield growth, either due to the closing of the yield gap between realized and potential yields (e.g. Cassman et *al.*, 2003; Ewert *et al.*, 2005; Lobell *et al.*, 2009), or due to policies such as stricter environmental regulation (e.g. Finger, 2010).

To date, there have been a limited number of reports (Kenny & Harrison, 1993) dealing with the changes expected in agroclimatic parameters at the pan-European scale, and many of these are review articles (Olesen & Bindi, 2002; Lavalle *et al.*, 2009; Olesen *et al.*, 2011). Conversely, various indications may be found in global-scale analyses that display the consequences of climate change for the whole of Europe considered as one large region (IFPRI, 2009) or two large entities (Parry *et al.*, 2004); these two studies directly estimated crop-yield changes using empirically calibrated crop-simulation models. They also provided quantitative estimates; however, these are linked to a fixed set of hypotheses intended to depict the key components of world crop production. Alternative approaches have considered sets of agroclimatic indices, with varying degrees of complexity (e.g. Fisher *et al.*, 2002, 2005; Ramankutty *et al.*, 2002). The latter studies offer comprehensive views of changes for Europe. However, these studies have had to rely on monthly datasets, whereas many key processes in agrosystems take place on daily and even shorter time scales. Therefore, the idea of elaborating an accessible and flexible tool allowing for the assessment of agroclimatic conditions (including the roles of variability and extremes) while keeping in mind the approaches being used has been progressively developed. Herein, we present a study aimed to provide a quantitative evaluation of agroclimatic conditions under present and projected climate-change conditions over most of the EU and neighboring countries with a special focus on variability and events with lower probability. For this purpose, we selected and applied a set of 11 agroclimatic indices to a new dataset of daily climatic data representing key agricultural regions of Europe.

Methods

Study area and data

The current study was confined to datasets of daily weather observations provided by members of the COST734 network. The data cover the period from 1971 to 2000 and were taken from weather stations representing the key agricultural regions of the given countries and provide continuous daily data, including maximum and minimum temperatures, global radiation (or sunshine duration), precipitation, mean daily relative air humidity and wind speed. In addition, these stations (when possible) were located outside urbanized areas. Such requirements significantly reduced the number of suitable sites, especially considering that all of the sites with <95% coverage (for each separate element) were excluded from the analysis. The included sites (Fig. 1) were then grouped according to their presence within particular environmental zones (EnZ) as defined by Metzger *et al.* (2005) and Jongman *et al.* (2006). The EnZ definitions herein cover 13 zones (Fig. 1) comprising 84 environmental strata (EnS), which are classified by monthly minimum and maximum temperatures, sum of

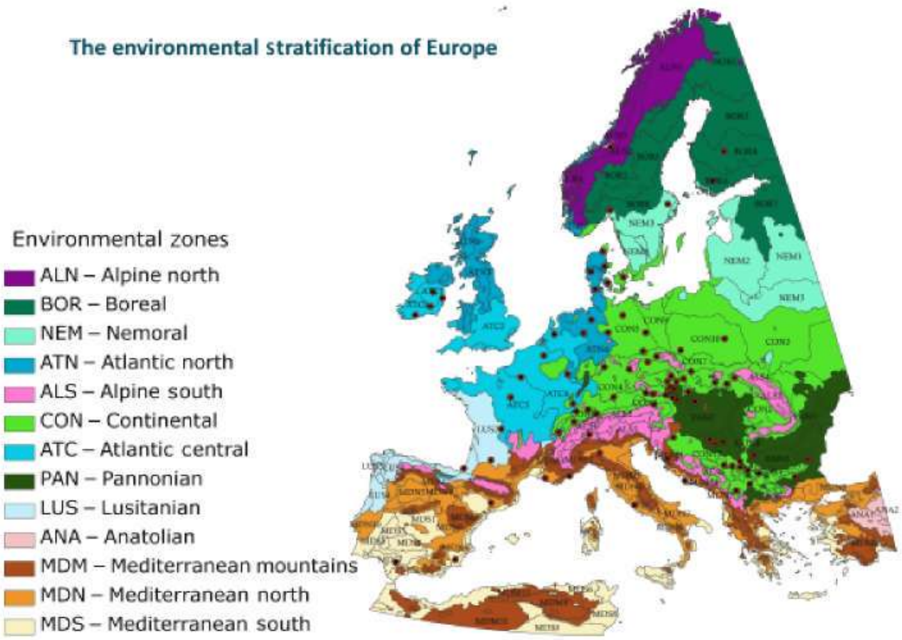


Fig. 1 EnZs in Europe according to Metzger *et al.* (2005) and Jongman *et al.* (2006) and sites where data were collected for the COST 734 database. The complete list of sites can be found in Appendix S1. Among the 13 EnZs, only the Anatolian zone was not considered because it is not technically located on the European continent; the Mediterranean mountains (MDM) and the Alpine north (ALN) zones were each represented by only one site.

precipitation, percentage of sunshine in months representing the four seasons (January, April, July and October) together with altitude, slope, northing and oceanicity. Overall, the strata accounting for 72% of all European agricultural land were represented by at least one climate station (Table 1). To simplify the figures, only the mean values for each EnZ are presented. To limit possible bias caused by the uneven representations of EnS, results were first averaged for each individual EnS and these means were used for the calculation of EnZ values.

Complete data were collected from 86 carefully screened sites from a total of 137 provided sites (Appendix S1), and the study domain covered the area between 8.5°W–27°E and 37–63.5°N. Nineteen European states are represented in the database, including the major agricultural producers of the EU; however, several important countries and regions (e.g. the eastern Mediterranean) were not covered due to a lack of data from these areas.

Agroclimatic indices

Figure 2 provides an overview of the methodological approach of using indicators for the evaluation of changes in agroclimatic conditions in Europe under climate change. To describe agroclimatic conditions, the 11 indicators described in Tables 2a and 2b were selected from a plethora of available options to represent the potential effects of weather on crop productivity and management. The selection was made from a 'short-list' of approximately 120 indices. The final set of indicators was required not only to represent potential productivity and growing conditions but also field workability as well as the occurrence of extreme events relevant to agriculture. This includes impacts as well as adaptation options for the different agricultural sectors. The study further focused on late frost and drought, as they were identified as major problems across most of Europe (Olesen *et al.*, 2011). In addition, each of the selected indices had to be applicable across all of the sites and be calculable from available datasets; furthermore, the portfolio was chosen so as to complement rather than repeat previous studies.

The daily reference (ET_r) and actual (ET_a) evapotranspiration values were calculated using the Penman–Monteith approach, as described in Allen *et al.* (1998), using modifications validated by Hlavinka *et al.* (in press). Crop growth on a given day was considered not to be significantly limited by water if the daily ratios of ET_a to ET_r exceeded 0.4–0.5 (FAO, 1979; Fisher *et al.*, 2002; Eliasson *et al.*, 2007). To limit eventual overestimation of water shortage, the lower end of the range (0.4) was applied here. The temperature thresholds used rely on the works of Chmielewski & Köhn (2000), Mitchell & Hulme (2002) and Larcher (2003), and were similar to those used by Fisher *et al.* (2002).

The Huglin index represents the thermal suitability for wine production and includes a correction factor for latitude as described by Huglin (1978). This index allows for characterizations of the suitability of viticulture in general and particular grapevine cultivars at a given location. A constraint of this index is that it does not consider cold-temperature limitations, which are critical for continental climates, and other

Table 1 Overview of the COST 734 database. The agricultural areas in the European states presented in Fig. 1 are based on the Corine land cover CLC2000-9/2007 and a 100 m resolution (copyright EEA, Copenhagen, 2007*). Only areas with agricultural land consisting of strata that contained at least one weather station were included in this study

EnZ name	EnZ acronym	Agricultural area in the EnZ† (ha)	Share of agricultural area of total area (%)	Agricultural area represented by the database (%)	Number of stations	Number of strata represented/ total number of strata	Countries in the EnZ‡
Alpine north	ALN	691 600	2.1	50	1	1/4	FI, NO, SE
Boreal	BOR	6 480 306	7.8	38	2	2/8	BY, EE, FI, LV, NO, RU, SE
Nemoral	NEM	10 836 063	21.8	18	2	1/5	BY, EE, FI, LV, LT, NO, PL, RU, SE
Atlantic north	ATN	16 642 613	57.1	70	6	2/5	DK, DE, GB, IE, IM, NL, NO
Alpine south	ALS	6 040 069	20.0	74	2	2/6	AD, AL, AT, BG, BA, CH, CZ, DE, GR, ES, FR, HR, IT, MK, ME, PL, RO, RE, SI, SK, UA
Continental	CON	57 900 681	46.4	96	36	10/12	AL, AT, BG, BY, BE, BA, CH, CZ, DE, DK, FR, HR, HU, LV, LI, LT, LU, MK, MD, ME, NL, NO, PL, RO, RS, RU, SE, SI, SK, UA
Atlantic central	ATC	40 180 988	79.4	100	13	5/5	BE, CH, DE, ES, FR, GB, IE, LU, NL
Pannonian	PAN	27 392 881	65.1	73	13	2/3	AT, BA, BG, CZ, DE, GR, FR, HR, MK, HU, MD, RO, RS, SI, SK, UA
Lusitanian	LUS	11 031 181	56.5	83	2	2/4	ES, FR, PT
Mediterranean mountains	MDM	8 922 394	16.4	4	1	1/11	AL, BA, BG, CH, GR, ES, FR, HR, IT, MK, HU, ME, PT, SI
Mediterranean north	MDN	26 560 575	50.7	32	4	3/10	AL, BA, BG, GR, ES, FR, HR, IT, MK, ME, PT, SI, TR
Mediterranean south	MDS	21 214 125	37.4	71	4	4/9	AL, ES, FR, GR, IT, MT, PT

*http://www.eea.europa.eu

†Data from Fig. 1.

‡Countries at least partly included in the zone are identified by internet country code.

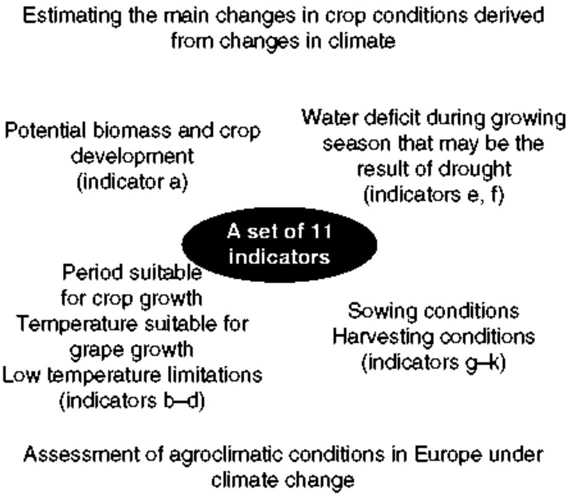


Fig. 2 Overview of the methodological approach to using indicators for the evaluation of changes in agroclimatic conditions in Europe under climate change.

limitations such as sunshine duration, soil conditions and water availability. Local climatic variations based on orography may also alter these conditions significantly.

The thresholds for sowing and harvest suitability (Table 2a) were based on published literature and tested using the observed sowing and harvest dates for spring barley, winter wheat and maize at 30 experimental stations at in the Czech Republic over a period of 20 years. The approach used is broadly in agreement with similar studies by Leenhardt & Lemaire (2002) and Maton *et al.* (2007). The soil-moisture thresholds used to define the suitable days for sowing and harvesting were stricter than those used by Rounsevell (1993) and Cooper *et al.* (1997), as no soil compaction or soil-structure damage should occur in sustainable agricultural systems. Across all of the investigated sites, the sowing and harvesting windows were held constant despite the varying relevance of some of these windows.

The agroclimatic parameters listed in Tables 2a and 2b were calculated with the use of a software package, AGRICLIM (Trnka *et al.*, 2010a), which is available from the authors. For all of the ET_r and ET_a calculations, spring barley was used as

Table 2a Overview of the indices used in the study

Agroclimatic factors	Indicator name (units)	Indicator description	Symbol
Potential biomass and crop development	Sum of effective global radiation (MJ m^{-2} $season^{-1}$)	Sum of global radiation of days with daily mean temperature >5 °C, daily minimum temperature >0 °C, ET_a*/ET_r† ratio >0.4 and no snow cover‡	a
Time period suitable for crop growth	Sum of effective growing days (days)	Number of days with daily mean temperature >5 °C, daily minimum temperature >0 °C, no snow cover and an ET_a/ET_r ratio >0.4	b
Temperature suitable for grape growth	Huglin index (unitless)	Thermal suitability for grape production, for the period from 1 April to 30 September	c
Low temperature limitations	Date of the last frost [date (from January 1st)]	Last occurrence of a daily minimum temperature of <-0.1 °C in the given season before June 30th	d
Water deficit during growing season that may be the result of drought	Number of days with water deficits from April to June (days)	All days within the given period with ET_a/ET_r of <0.4	e
	Number of days with water deficits from June to August (days)	Same as e	f
Harvesting conditions	Proportion of suitable days for harvesting in June (unitless)	All days with soil-water content in the top 0.1 m between 10% and 70% of the maximum soil water-holding capacity (SWC), with precipitation on the given day ≤ 1 mm and precipitation on the preceding day ≤ 5 mm	g
	Proportion of suitable days for harvesting in July (unitless)	Same as g	h
Sowing conditions that will affect the growing season	Proportion of suitable days for sowing from March 1st to April 25th (early spring) (unitless)	All days with soil-water content in the top 0.1 m between 10% and 70% of the maximum soil water-holding capacity (SWC), mean daily temperature on the given day and on the preceding day >5 °C, without snow cover and with precipitation on the given day ≤ 1 mm and precipitation on the preceding day ≤ 5 mm	i
	Proportion of suitable days for sowing from April 26th to May 20th (late spring) (unitless)	Same as i	j
	Proportion of suitable days for sowing from September 15th to November 30th (fall) (unitless)	Same as i	k

*ET_a refers to actual evapotranspiration calculated from spring C3 crop (spring barley) assuming a soil water-holding capacity of 0.27 m and a maximum rooting depth of 1.3 m (more details in the text).

†ET_r refers to the same crop surface as for ET_a but for reference evapotranspiration; the crop parameters were set according to Allen *et al.* (1998).

‡Snow cover was estimated using a model validated by Trnka *et al.* (2010a, b).

the reference crop surface because it is grown in all the investigated EnZs. When calculating the status of the available soil water, homogenous soil properties were assumed throughout the profile (top and subsoil). The soil water-holding capacity in the top 0.1 m of soil was assumed to be 0.02 m and the capacity in the entire profile (a 1.3 m soil depth) was 0.27 m. Although soil water-holding capacity (as well as other soil parameters) differed across the investigated sites, a uniform soil profile was used to allow station-to-station comparisons. When calculating evapotranspiration, an adjustment for atmospheric CO_2 concentration was made using the method proposed by Kruijt *et al.* (2008) using the CO_2 concentrations listed in Table 3.

Creating daily weather series under baseline and climate-change conditions

A restriction on the datasets provided meant that it was not possible to directly apply the observations. Instead, the data were used to train a stochastic weather generator (WG) M&Rfi (Dubrovský *et al.*, 2004), and a 99-year stochastic daily weather series of global radiation sum, maximum and minimum temperatures, precipitation sum, mean relative air humidity and wind speed were prepared to represent the baseline (1971–2000) climate conditions for each site. In the next step, the baseline WG parameters were perturbed according to the climate-change scenarios (Fig. 3) and used as inputs to the AGRICLIM model.

Table 2b Overview of the key parameters of each index and threshold values used in the study

Symbol	Indicator name (units)	Parameter*	Value†/response (mean ± std)‡	
a	Sum of effective global radiation	T_{mean}§ = 5 °C	6 °C/−4 ± 2%	4 °C/ + 3 ± 2%
	(MJ m^{-2} $season^{-1}$)	$ET_a/ET_r<0.4$	0.5/−24 ± 11%	0.3/ + 22 ± 14%
		Crop¶ = sb	ww/ + 2 ± 7%	gs/−15 ± 17%
b	Sum of effective growing days (days)	T_{mean}§ = 5 °C	6 °C/−15 ± 8 days	4 °C/ + 8 ± 4 days
		$ET_a/ET_r<0.4$	0.5/−37 ± 13 days	0.3/ + 30 ± 14 days
		Crop¶ = sb	ww/ + 11 ± 9 days	gs/−26 ± 26 days
c	Huglin index (unitless)	Effect of latitude	No effect/−2 ± 1%	
d	Date of the last frost [date (from January 1st)]	T_{min}‖ < −0.1 °C	+ 0.5/4 ± 2 days	−0.5/−3 ± 2 days
e	Number of days with water deficits	$ET_a/ET_r<0.4$	0.5/−12 ± 6 days	0.3/ + 9 ± 5 days
	from April to June (days)	Crop = sb	ww/−6 ± 13 days	gs/ + 2 ± 14 days
f	Number of days with water deficits	$ET_a/ET_r<0.4$	0.5/−14 ± 7 days	0.3/ + 11 ± 8 days
	from June to August (days)	Crop = sb	ww/ + 5 ± 7 days	gs/ + 12 ± 9 days
g	Proportion of suitable days for	SWC range**	0–75%/0 ± 0 days	0–65%/0 ± 0 days
	harvesting in June (unitless)	= 0–70%	5 mm/ + 4 ± 1 days	No rain‡‡/−4 ± 1 days
h	Proportion of suitable days for	Precip (*n*)†† = 1 mm	0–75%/0 ± 0 days	0–65%/0 ± 0 days
	harvesting in July (unitless)		5 mm/ + 3 ± 1 days	No rain/−3 ± 1 days
i	Proportion of suitable days for	SWC range**	5–75%/−1 ± 1 days	15–65%/−3 ± 3 days
	sowing from March 1st through April 25th	= 10–70%	5 mm/ + 5 ± 2 days	No rain‡‡/−5 ± 2 days
	(early spring) (unitless)	Precip (*n*)†† = 1 mm		
j	Proportion of suitable days for sowing from		5–75%/−1 ± 1 days	15–65%/−1 ± 2 days
	April 26th through May 20th		5 mm/ + 3 ± 1 days	No rain/−3 ± 1 days
	(late spring) (unitless)			
k	Proportion of suitable days for sowing from		5–75%/−2 ± 2 days	15–65%/−4 ± 3 days
	September 15th through November 30th		5 mm/ + 6 ± 2 days	No rain/−5 ± 2 days
	(early spring) (unitless)			

In the right-most column an overview of the effects of modifying the parameter values is given as the mean (± standard deviation) shift of the given indicator across all sites included in the study.

*List of parameters of each indicator changed in the sensitivity runs including their initial values used in the study.

†Value refers to the threshold used in the sensitivity run.

‡The response (mean and standard deviation) refers to the difference between the threshold/assumption used in the study and the changed value indicated before the slash.

§T_{mean} – threshold of daily mean air temperature at 2 m.

¶Change in the crop yield affects the calculation of ET_a and ET_r, where 'sb' refers to spring barley, 'ww' to winter wheat and 'gs' to grassland with a maximum of three cuts per year.

‖T_{min} – threshold of daily minimum air temperature at 2 m.

**SWC range – the range of soil-moisture content in which soil-tilling operations are considered possible.

††Precip – threshold of precipitation on the given day.

‡‡No rain – daily sum of rainfall $\leq$ 0.1 mm.

Climate-change scenarios for this study were developed by means of a 'pattern-scaling' technique (Santer *et al.*, 1990) from the outputs of the Global Climate Models (GCMs) and were then used to modify the parameters of the WG (as used in, e.g., Trnka *et al.*, 2004). The 'pattern-scaling' technique defines a climate-change scenario as the product of the standardized scenario and the change in global mean temperature. The standardized scenarios (Fig. 3) relate the responses of climatic characteristics to a 1 °C rise in global mean temperature (ΔT_G). They were determined by applying a regression method (Dubrovský *et al.*, 2005) to the 2000–2099 period, which was obtained from the GCM simulations that had been run with the SRES-A2 (Special Report on Emission Scenarios) emission scenario for the IPCC Fourth Assessment Report (Nakicenovic *et al.*, 2000; Solomon *et al.*, 2007). The projected changes in ΔT_G at 2030 and 2050 were calculated via a simple climate model, MAGICC (Harvey *et al.*, 1997; Hulme *et al.*, 2000), assuming the A2 emission scenario and medium or high climate sensitivity (Table 3). As a 'worst-case scenario,' we also assessed changes under a mean global temperature increase of 5 °C. As the role of the climate-sensitivity factor on temperature change by 2050 was relatively small (Table 3), the responses of agroclimatic indices were similar and, therefore, we chose to report the results for the higher sensitivity only.

The three GCMs utilized were ECHAM5/MPI-OM (ECHAM), HadCM3 (HadCM) and NCAR-PCM (NCAR). Apart from representing inter-GCM variability quite well (Table 4),

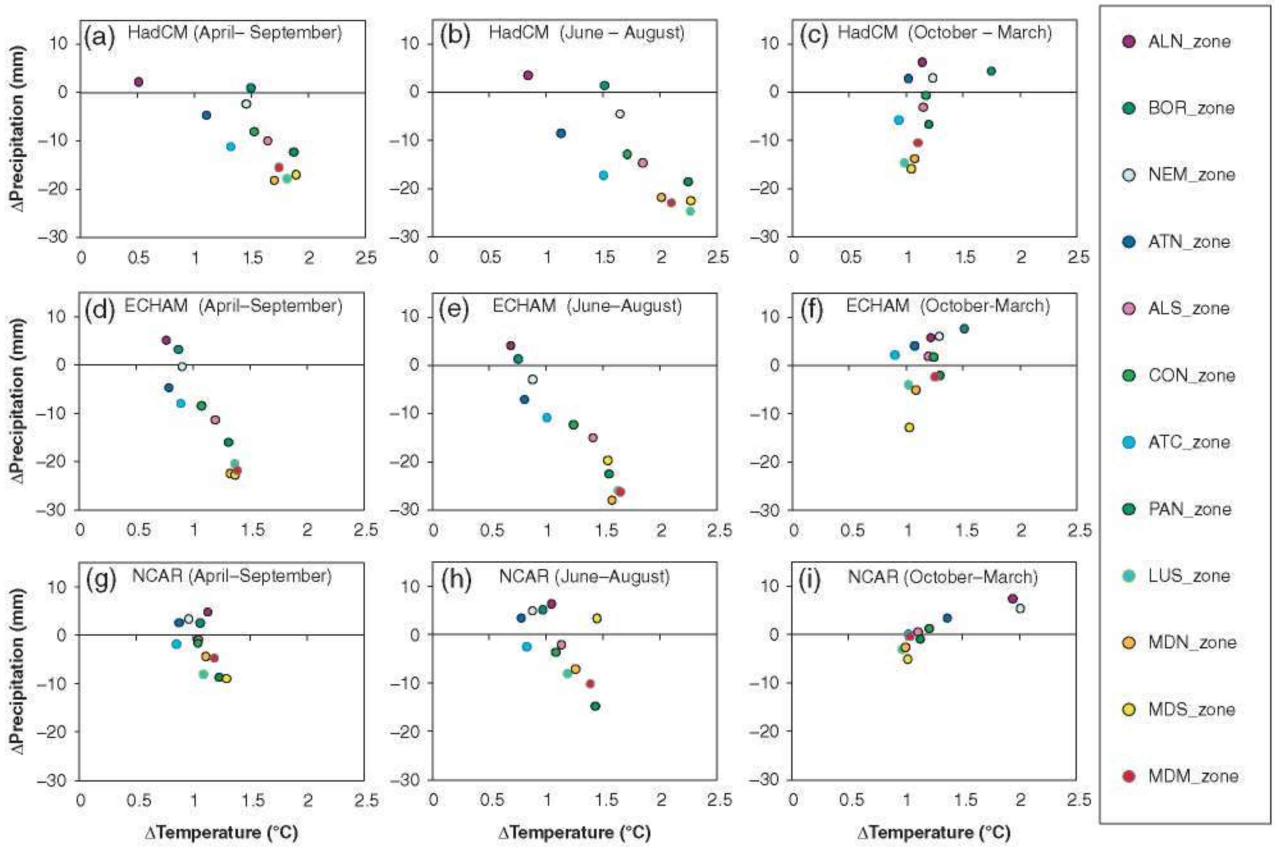


Fig. 3 Projected changes in mean temperature and precipitation during different seasons [April–September (a, d, g), June–August (b, e, h) and October–March (c, f, i)] for individual zones as a response to a 1 °C global warming (compared with 1971–2000). Three GCMs (ECHAM5, HadCM and NCAR-PCM) are presented. The dots represent mean temperature and precipitation changes based on individual stations in their respective EnZs. The product of a 1 °C warming response and the estimated value of global mean temperature (Table 3) provide absolute values of the changes used to perturb WG parameters.

Table 3 Overview of the scenarios considered in this study, their associated atmospheric CO_2 concentrations and global mean temperature values

Scenario name	Time period	Socioeconomic SRES scenario driving GCM runs	Climate system sensitivity to $2 \times CO_2$ concentrations	Scenario projected CO_2 concentration (ppm)	Scenario estimated change of mean global temperature (°C)
2030_med	2030	A2	Medium	451	~ + 0.81
2030_high			High	458	~ + 1.03
2050_med	2050		Medium	533	~ + 1.49
2050_high			High	536	~ + 1.90
5 °C	–	–	–	900	+ 5.00

Medium climate sensitivity indicates that an equilibrium change in global mean surface temperature following a doubling of the atmospheric equivalent CO_2 concentration is 3.0 °C, whereas it is 4.5 °C under high climate sensitivity.

these three GCMs (or previous versions thereof) have been used in a number of impact studies and have generally performed well in reproducing baseline climates in various European regions (e.g. Dubrovský *et al*., 2005).

Results

Figures 4–6 and Table 5 present the main results of the study (the EnZ acronyms are defined in Table 1 and

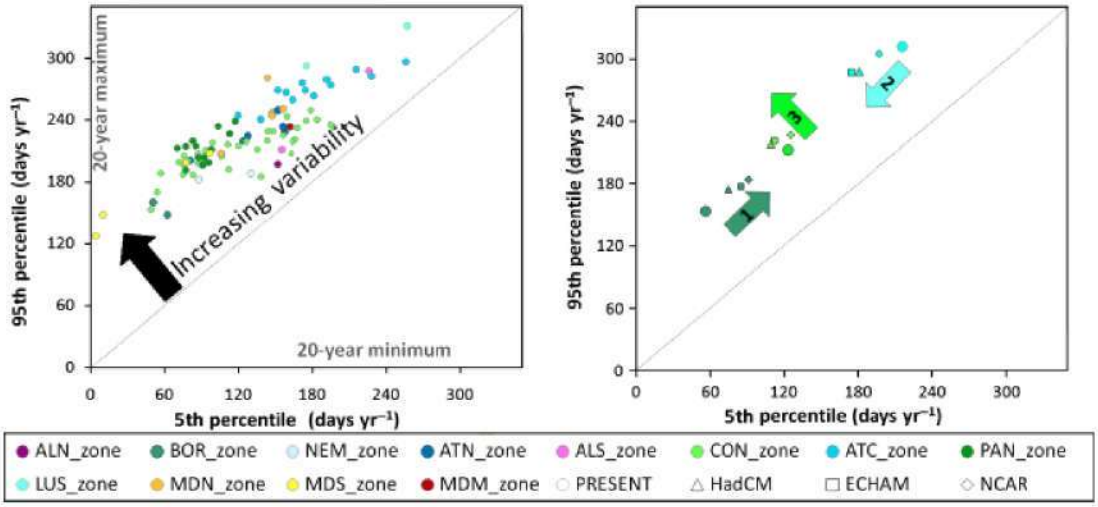


Fig. 4 Aggregation of results from the station to the EnZ level using the duration of the effective growing season (indicator – b) as an example. The left panel shows the calculation of the indicator values for the 95th and 5th percentiles for the 86 sites under the 1971–2000 climate conditions. The right panel illustrates a shift in the mean value of the indicator for the three climate-change scenarios considered and a graphical interpretation of the results. In the BOR zone (1), the indicator increased in both the 20-year minima and maxima, with small changes in the variability. In the LUS zone (2), the indicator decreased in both the 20-year minima and maxima. In the CON zone (3), the indicator increased in the 20-year maximum and showed stagnation or a decrease in terms of the 20-year minimum, which also indicates increased variability.

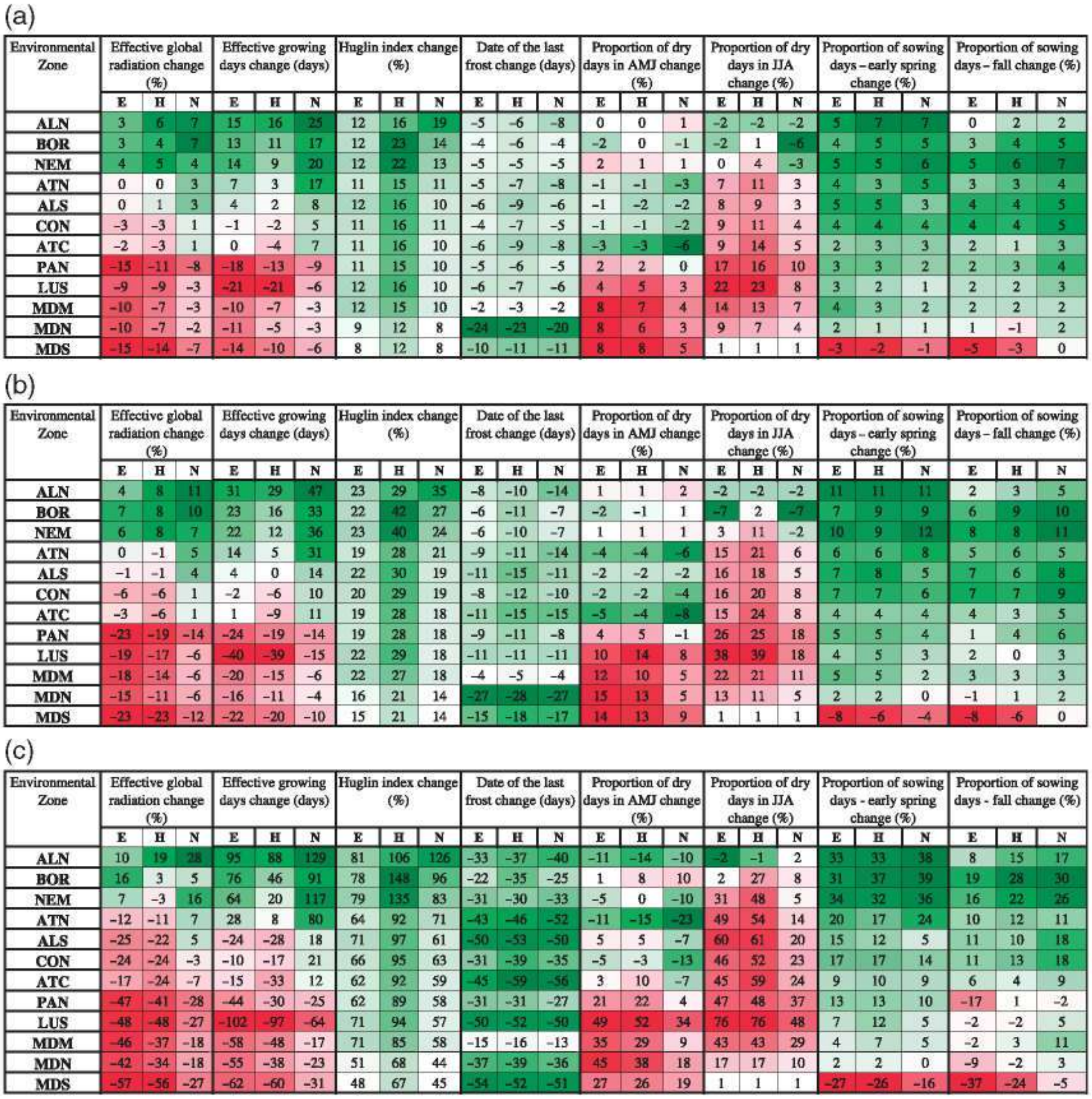
Fig. 1). Figure 4 explains the process of aggregating the results, Fig. 5 shows the projected changes in individual indicators under different scenarios and Fig. 6 shows the present values for each EnZ as well as estimates according to the SRES-A2 medium climate sensitivity for 2050. Because the study was based on daily data and high-number (99) runs for each site, as well as estimating the central (median) values, changes in the 20-year minima and maxima of the agroclimatic indicators were also assessed to illustrate changes in variability. Aggregations of the site results from the station to the EnZ level are presented in detail in Fig. 4.

Projected changes in agroclimatic parameters by 2030 and 2050

Figure 3, in combination with Table 4, indicates how overall climatic conditions might change and illustrates change patterns among the seasons and GCMs. More pronounced warming and decreased precipitation between April and September were found for the Mediterranean mountains (MDM), Lusitanian (LUS), Pannonian (PAN), Mediterranean north (MDN) and Mediterranean south (MDS) zones than in the Boreal (BOR) and Alpine north (ALN) zones. The overall patterns of change are consistent for all three GCMs in most zones, except for the colder half of the year. HadCM showed higher changes in temperature and ECHAM more pronounced changes in precipitation, while NCAR showed moderate temperature changes for both in summer, with larger temperature increases in Nemoral (NEM) and ALN during the colder half of the year.

Effective global radiation and effective growing days. During periods of increased drought stress, there was a marked decrease in effective global radiation sums (and thus of potential crop productivity under rainfed conditions) in the MDS, MDN, MDM, PAN and LUS zones (Fig. 5). Increased interannual variability can be seen in the Atlantic north (ATN), Continental (CON) and NEM zones (Fig. 6a and b). An increase of effective global radiation was projected in the BOR, NEM and ALN zones; however, these zones have, in general, less suitable soils and topography. The overall reductions in rainfed production potential, which are expressed in terms of usable global radiation, were quite marked and in line with the changes in the number of effective growing days (Fig. 6b).

Huglin index. Figure 3 shows that temperatures were projected to increase throughout the study region during the period from April to September and, therefore, Huglin indices are also expected to considerably increase across all of the investigated zones (Figs 5a and b, 6c). By 2050, most of the sites in the Alpine south (ALS), MDM, CON and Atlantic



(a)

Environmental Zone	Effective global radiation change (%)			Effective growing days change (days)			Huglin index change (%)			Date of the last frost change (days)			Proportion of dry days in AMJ change (%)			Proportion of dry days in JJA change (%)			Proportion of sowing days – early spring change (%)			Proportion of sowing days – fall change (%)		
	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N
ALN	3	6	7	15	16	25	12	16	19	−5	−6	−8	0	0	1	−2	−2	−2	5	7	7	0	2	2
BOR	3	4	7	13	11	17	12	23	14	−4	−6	−4	−2	0	−1	−2	1	−6	4	5	5	3	4	5
NEM	4	5	4	14	9	20	12	22	13	−5	−5	−5	2	1	1	0	4	−3	5	5	6	5	6	7
ATN	0	0	3	7	3	17	11	15	11	−5	−7	−8	−1	−1	−3	7	11	3	4	3	5	3	3	4
ALS	0	1	3	4	2	8	12	16	10	−6	−9	−6	−1	−2	−2	8	9	3	5	5	3	4	4	5
CON	−3	−3	1	−1	−2	5	11	16	11	−4	−7	−5	−1	−1	−2	9	11	4	4	4	4	4	4	5
ATC	−2	−3	1	0	−4	7	11	16	10	−6	−9	−8	−3	−3	−6	9	14	5	2	3	3	2	1	3
PAN	−15	−11	−8	−18	−13	−9	11	15	10	−5	−6	−5	2	2	0	17	16	10	3	3	2	2	3	4
LUS	−9	−9	−3	−21	−21	−6	12	16	10	−6	−7	−6	4	5	3	22	23	8	3	2	1	2	2	3
MDM	−10	−7	−3	−10	−7	−3	12	15	10	−2	−3	−2	8	7	4	14	13	7	4	3	2	2	2	2
MDN	−10	−7	−2	−11	−5	−3	9	12	8	−24	−23	−20	8	6	3	9	7	4	2	1	1	1	−1	2
MDS	−15	−14	−7	−14	−10	−6	8	12	8	−10	−11	−11	8	8	5	1	1	1	−3	−2	−1	−5	−3	0

(b)

Environmental Zone	Effective global radiation change (%)			Effective growing days change (days)			Huglin index change (%)			Date of the last frost change (days)			Proportion of dry days in AMJ change (%)			Proportion of dry days in JJA change (%)			Proportion of sowing days – early spring change (%)			Proportion of sowing days – fall change (%)		
	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N
ALN	4	8	11	31	29	47	23	29	35	−8	−10	−14	1	1	2	−2	−2	−2	11	11	11	2	3	5
BOR	7	8	10	23	16	33	22	42	27	−6	−11	−7	−2	−1	1	−7	2	−7	7	9	9	6	9	10
NEM	6	8	7	22	12	36	23	40	24	−6	−10	−7	1	1	1	3	11	−2	10	9	12	8	8	11
ATN	0	−1	5	14	5	31	19	28	21	−9	−11	−14	−4	−4	−6	15	21	6	6	6	8	5	6	5
ALS	−1	−1	4	4	0	14	22	30	19	−11	−15	−11	−2	−2	−2	16	18	5	7	8	5	7	6	8
CON	−6	−6	1	−2	−6	10	20	29	19	−8	−12	−10	−2	−2	−4	16	20	8	7	7	6	7	7	9
ATC	−3	−6	1	1	−9	11	19	28	18	−11	−15	−15	−5	−4	−8	15	24	8	4	4	4	4	3	5
PAN	−23	−19	−14	−24	−19	−14	19	28	18	−9	−11	−8	4	5	−1	26	25	18	5	5	4	1	4	6
LUS	−19	−17	−6	−40	−39	−15	22	29	18	−11	−11	−11	10	14	8	38	39	18	4	5	3	2	0	3
MDM	−18	−14	−6	−20	−15	−6	22	27	18	−4	−5	−4	12	10	5	22	21	11	5	5	2	3	3	3
MDN	−15	−11	−6	−16	−11	−4	16	21	14	−27	−28	−27	15	13	5	13	11	5	2	2	0	−1	1	2
MDS	−23	−23	−12	−22	−20	−10	15	21	14	−15	−18	−17	14	13	9	1	1	1	−8	−6	−4	−8	−6	0

(c)

Environmental Zone	Effective global radiation change (%)			Effective growing days change (days)			Huglin index change (%)			Date of the last frost change (days)			Proportion of dry days in AMJ change (%)			Proportion of dry days in JJA change (%)			Proportion of sowing days - early spring change (%)			Proportion of sowing days - fall change (%)		
	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N	E	H	N
ALN	10	19	28	95	88	129	81	106	126	−33	−37	−40	−11	−14	−10	−2	−1	2	33	33	38	8	15	17
BOR	16	3	5	76	46	91	78	148	96	−22	−35	−25	1	8	10	2	27	8	31	37	39	19	28	30
NEM	7	−3	16	64	20	117	79	135	83	−31	−30	−33	−5	0	−10	31	48	5	34	32	36	16	22	26
ATN	−12	−11	7	28	8	80	64	92	71	−43	−46	−52	−11	−15	−23	49	54	14	20	17	24	10	12	11
ALS	−25	−22	5	−24	−28	18	71	97	61	−50	−53	−50	5	5	−7	60	61	20	15	12	5	11	10	18
CON	−24	−24	−3	−10	−17	21	66	95	63	−31	−39	−35	−5	−3	−13	46	52	23	17	17	14	11	13	18
ATC	−17	−24	−7	−15	−33	12	62	92	59	−45	−59	−56	3	10	−7	45	59	24	9	10	9	6	4	9
PAN	−47	−41	−28	−44	−30	−25	62	89	58	−31	−31	−27	21	22	4	47	48	37	13	13	10	−17	1	−2
LUS	−48	−48	−27	−102	−97	−64	71	94	57	−50	−52	−50	49	52	34	76	76	48	7	12	5	−2	−2	5
MDM	−46	−37	−18	−58	−48	−17	71	85	58	−15	−16	−13	35	29	9	43	43	29	4	7	5	−2	3	11
MDN	−42	−34	−18	−55	−38	−23	51	68	44	−37	−39	−36	45	38	18	17	17	10	2	2	0	−9	−2	3
MDS	−57	−56	−27	−62	−60	−31	48	67	45	−54	−52	−51	27	26	19	1	1	1	−27	−26	−16	−37	−24	−5

Fig. 5 Changes in the median values of selected agroclimatic indicators relative to the 1971–2000 reference period for: (a) 2030, assuming the SRES-A2 scenario and a medium system climate sensitivity; (b) the same as (a) but for 2050; and (c) for global warming by 5 °C. The color shading represents the positive (green) and negative (red) impacts of these changes and the values represent the medians of all of the sites in a particular zone. The estimates are based on three GCMs, i.e., the ECHAM (E), HadCM (H) and NCAR (N). The proportion of dry days was calculated for April–June (AMJ) and June–August (JJA).

central (ATC) zones will achieve Huglin-index levels that are typical of wine-producing zones.

Date of the last frost. Earlier dates for the last frost were projected in all of the investigated zones (Figs 5 and 6d), although the extent to which these dates changed differed among individual zones. In the ATN, ATC, MDS, ALS and MDN zones, considerably longer frost-free periods were projected, and a larger degree of interannual variability was projected for the ALS and ATC zones.

Number of days with water deficit. The probability of the occurrence of days with water deficit (i.e. an ET_a/ET_r ratio <0.4) from April to June was projected to increase in the LUS, MDM, MDS and MDN zones (Figs 5 and 6e), whereas the most prominent increases in April–June drought variability were projected in the LUS and PAN zones. The changes in the June–August droughts were much more uniform in most zones (except ALN and BOR), showing a profound increase in drought duration (Fig. 5) and also variability (in the case of the CON, ATC, LUS, ALS and PAN zones).

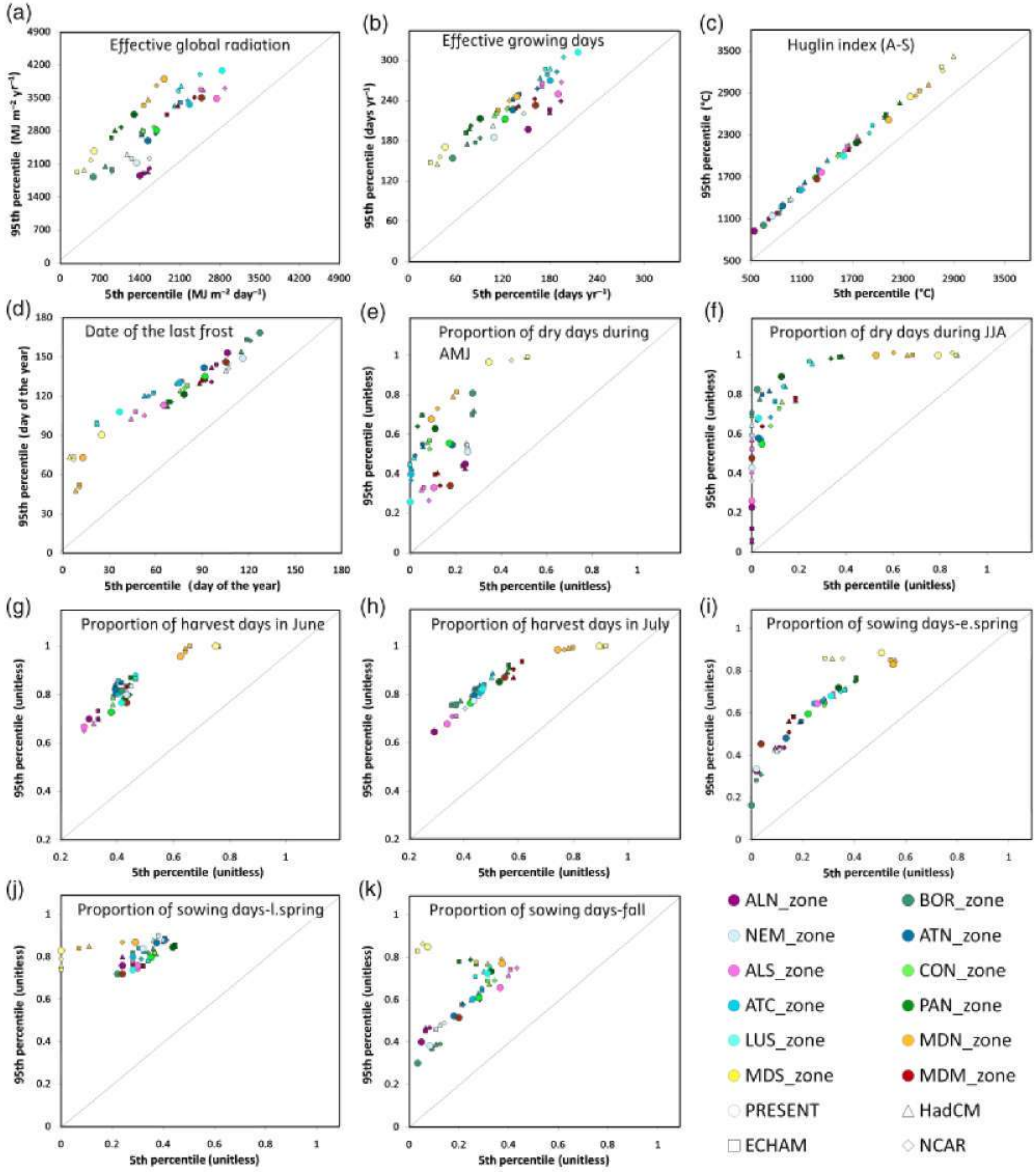


Fig. 6 The values of the (a) effective global radiation, (b) number of effective growing days, (c) Huglin index and (d) frost risk under the present (1971–2000) climate conditions (circles) and those projected assuming a medium climate sensitivity using the A2 emission scenario for 2050. The marks represent the means of the given site indices of each EnZ; (e) the proportion of dry days from April to June and (f) from June to August and the proportion of suitable harvest days in June (g) and July (h); the proportion of suitable sowing days during the early spring (i), late spring (j) and fall (k) sowing windows. The early-spring sowing window is defined as the period from March 1st through April 25th (55 days) and the late-spring sowing window from April 26th through May 20th (25 days). The autumn sowing window ranges from September 15th through November 30th (76 days) (see legend).

Table 4 Estimated changes of the mean temperature and precipitation at individual sites averaged over the EnZ for three selected GCMs compared with an ensemble of 14 GCM runs for which SRES-A2 runs were available (see notes for more details)

	Mean Δ of temperature April–September (°C)						Mean Δ of precipitation April–September (%)						Mean Δ of temperature October–March (°C)						Mean Δ of precipitation October–March (%)					
	Models used in the study			14 GCM with SRES-A2 run			Models used in the study			14 GCM with SRES-A2 run			Models used in the study			14 GCM with SRES-A2 run			Models used in the study			14 GCM with SRES-A2 run		
Environmental zone	H	E	N	Min	Avg	Max	H	E	N	Min	Avg	Max	H	E	N	Min	Avg	Max	H	E	N	Min	Avg	Max
ALN	2.0	1.7	2.4	1.1	2.0	3.3	9	10	11	8	11	19	2.3	2.6	3.9	2.2	3.0	4.0	3	14	22	0	16	26
BOR	3.2	1.9	2.3	1.4	2.4	3.8	5	10	7	−4	8	24	3.5	3.1	5.1	2.4	3.8	5.5	16	14	19	6	16	25
NEM	3.1	2.0	2.1	1.6	2.3	3.5	1	2	9	−9	5	11	2.6	2.7	3.9	2.2	3.0	4.1	12	12	12	5	13	19
ATN	2.4	1.7	1.9	1.6	2.1	2.7	−5	−6	8	−16	−1	9	2.2	2.3	2.8	1.9	2.3	2.8	9	7	7	0	10	19
ALS	3.4	2.6	2.2	2.1	2.7	3.4	−15	−15	2	−16	−8	5	2.5	2.7	2.6	1.9	2.4	2.9	6	8	−4	−5	2	8
CON	3.3	2.4	2.2	2.1	2.6	3.3	−11	−11	1	−16	−7	5	2.6	2.7	2.7	2.1	2.4	3.0	7	4	−2	−2	3	7
ATC	2.7	2.0	1.8	1.7	2.2	2.8	−19	−12	−3	−21	−11	0	2.0	2.1	2.4	1.6	2.0	2.4	5	5	1	1	4	12
PAN	4.0	2.9	2.6	2.2	3.0	4.0	−19	−22	−12	−25	−14	−3	2.8	2.8	2.5	1.9	2.4	3.0	8	−1	−10	−11	−2	8
LUS	3.8	2.6	2.4	2.1	3.0	4.0	−30	−27	−15	−30	−21	−4	2.2	2.3	2.4	1.6	2.2	2.7	−1	−6	−7	−14	−5	2
MDN	3.9	3.0	2.5	2.3	3.0	3.9	−25	−27	−8	−28	−16	−5	2.6	2.9	2.4	1.7	2.4	3.0	10	5	−7	−8	1	10
MDM	3.6	2.9	2.4	2.3	2.9	3.6	−27	−30	−8	−31	−19	−7	2.4	2.6	2.3	1.6	2.3	2.8	4	1	−6	−11	−2	10
MDS	3.9	3.0	2.8	2.5	3.2	3.9	−29	−39	−17	−39	−22	−8	2.4	2.5	2.4	1.7	2.3	2.8	−10	−17	−5	−20	−12	−3

Values represent estimates based on the assumption of high climate sensitivity for the target year 2050.

ECHAM (E), HadCM (H) and NCAR (N).

The 14 GCM models used to develop the ranges of GCM projections included BCM2.0 (Bjerknes Centre for Climate Research, Norway), CGMR (Canadian Center for Climate Modeling and Analysis, Canada), CNCM3 (Centre National de Recherches Meteorologiques, France), CSMK3 (Australia's Commonwealth Scientific and Industrial Research Organization, Australia), MPEH5 (Max-Planck-Institute for Meteorology, Germany), ECHOG (Meteorological Institute University, Bonn, Germany + Meteorological Research Institute, Korea + Model and Data Group at Max-Planck-Institute for Meteorology, Germany), GFCM20 (Geophysical Fluid Dynamics Laboratory, USA), INCM3 (Institute for Numerical Mathematics, Russia), MIMR (National Institute for Environmental Studies, Japan), MRCGCM (Meteorological Research Institute, Japan), PCM and NCCCSM (National Center for Atmospheric Research, USA), HADCM3 and HADGEM (UK Met. Office, UK) and data were downloaded from http://www.mad.zmaw.de/IPCC_DDC/html/SRES_AR4/index.html

Table 5 The 5th-, 50th- and 95th-percentile values of the selected agroclimatic indices during the period from 1971 to 2000

	Effective global radiation (MJ m^{-2} yr^{-1})			Effective growing days (days yr^{-1})			Huglin index (unitless)			Date of the last frost (day of the year)			Proportion of dry days in AMJ (%)			Proportion of dry days in JJA (%)			Proportion of sowing days – early spring (%)			Proportion of sowing days – fall (%)		
Environmental zone	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th	5th	50th	95th
ALN	1398	1603	1855	152	174	197	541	731	932	106	128	153	24	32	45	0	2	23	2	13	33	5	18	40
BOR	581	1417	1824	57	115	154	650	828	1014	127	146	169	27	46	81	2	31	83	0	5	16	3	17	30
NEM	1339	1831	2127	109	157	185	751	953	1143	116	132	149	25	37	51	0	7	43	2	14	34	8	20	38
ATN	1536	2187	2596	133	190	226	874	1078	1293	91	117	142	18	36	55	3	14	58	13	30	48	18	33	53
ALS	2744	3213	3486	191	227	250	1332	1560	1770	65	90	113	10	16	33	0	3	26	25	44	65	37	50	66
CON	1693	2296	2812	123	172	212	1267	1485	1691	92	113	135	17	35	55	4	23	55	22	41	60	28	45	61
ATC	2273	2918	3360	180	235	270	1087	1313	1512	75	106	130	0	21	40	4	21	57	24	44	65	26	43	60
PAN	1298	2264	3143	91	154	213	1745	1978	2191	78	101	121	11	32	63	13	50	89	34	55	72	33	57	73
LUS	2843	3577	4079	216	276	312	1594	1813	2000	37	79	108	0	4	26	3	24	68	31	50	68	32	52	73
MDN	2161	2795	3434	159	201	242	1585	1795	1964	53	61	100	16	30	51	33	51	74	33	50	65	28	51	69
MDM	1811	2856	4083	132	191	244	2207	2422	2605	17	48	80	7	37	68	48	83	100	53	68	82	38	58	74
MDS	596	1470	2371	47	113	171	2382	2647	2852	25	56	91	35	72	97	79	99	100	50	75	89	8	59	85

These values represent the means of the values per given percentile from all of the sites in a given zone.

Suitability for harvesting. The proportion of suitable harvest days in June (Fig. 6g) was projected to remain high or to increase in the MDN and MDS zones. In the majority of the other zones (e.g. LUS, NEM, MDM and CON), the mean number of suitable harvest days increased together with their variability. In the ALS and ALN zones, the proportion of suitable days in June remained rather low, which is relevant for grassland, forage crops and vegetables grown in these regions. July harvesting conditions (Fig. 6h) were projected to improve in most zones but to worsen for NCAR projections in the BOR and NEM zones.

Suitability for sowing. The number of suitable days for sowing in defined sowing windows was projected to decrease in the MDS and partly in the MDN regions (Figs 5 and 6i and k). This is due to a considerable decrease in soil-moisture levels, especially in the topsoil, and sowing would still be feasible following irrigation. In the other zones, improved conditions were projected in the case of early-spring sowing (Fig. 6i). Changes in late spring sowing conditions were less consistent, indicating higher interseasonal variability (Fig. 6j). Autumn sowing conditions (Fig. 6k) showed increased variability in the PAN and LUS zones and substantial improvements in the ALN, BOR, NEM, ALS, CON, MDM, ATN and ATC zones.

Agroclimatic conditions under 5 °C warming

The projected change patterns in Fig. 5c are similar to those depicted in Fig. 5a and b, although here the changes (especially those that negatively affect the production potential) are more pronounced. In addition to the number of effective growing days, the effective global radiation was projected to decrease for all large agricultural zones investigated in this study except ATN (for the case of changes based on NCAR). Huglin-index values were projected to increase across all zones, reaching unprecedented levels in today's primary wine-growing regions, which may therefore become unsuitable for the currently planted grape varieties. Comparatively, the last frost was projected to occur, on average, much earlier in the year; however, there was also a marked increase in the interannual variability of the last frost date in the ATN, ATC, LUS and CON zones, which might maintain or even increase frost risk, e.g., for fruit trees, due to a concurrent shift to earlier flowering. The overall drying of most of the agriculturally important zones would be severe (especially during summer), with some zones facing the parallel challenge of higher water deficits and larger interannual variability. Most notable were the changes in water balances in the cases of the LUS and CON zones. There were significant improvements in the number of suitable days for harvest in June and July as well as for early sowing, except for the MDN and MDS zones. The late spring sowing window exhibited a large increase in interannual variability. The sowing of winter crops might become problematic because the proportion of suitable sowing days during autumn will vary dramatically in most zones. The areas that will benefit from a longer and more sustained autumn sowing window are those in the ALN, NEM, BOR and ATN zones.

Discussion

The environmental stratification of Metzger *et al.* (2005) and Jongman *et al.* (2006) clusters areas with similar environmental conditions via the use of a limited number of variables that may not sufficiently capture the large diversity of agroclimatic conditions across Europe. The values of the agroclimatic indices obtained from the stations in the southern zones (MDS and MDN in particular) were more internally consistent than those obtained from stations in other zones (Fig. 4a). There was also a pronounced difference in the behavior of sites in zones with large oceanic influences (ATN, ATC or LUS) compared with the continental climate of sites in the PAN zone. The largest internal variability was seen within the CON zone, which has the largest number (12) of strata (Metzger *et al.*, 2005); however, the stratification used provides the most detailed classification available based on climatic data from recent decades. Moreover, several studies have demonstrated a close relationship between the EnS (Ewert *et al.*, 2005; Smit *et al.*, 2008) or corresponding regions (Reidsma, 2007; Reidsma *et al.*, 2009) and the productivity of agricultural crops (e.g. maize, winter wheat or grassland).

We are aware that environmental conditions represent a continuum across space and time and that any attempt to stratify them inevitably leads to simplifications, which in turn may result in similar values for particular agroclimatic indicators across several zones. In fact, Metzger *et al.* (2005) reported that the first map of the EnS included dispersed scatter for small regions of only a few square kilometers and, therefore, all regions smaller than 250 km^2 were assigned to the strata of the neighboring grid cells. Despite these possible shortcomings, we view the clustering of sites in climate-change impact studies based on EnZ as a valuable complement to classifications based on administrative regions (e.g. Olesen & Bindi, 2002; Reidsma *et al.*, 2009) or other *ad hoc* classifications (e.g. Christensen & Christensen, 2007).

ALN

The ALN zone was represented by a single weather station, which is located in the largest agricultural area within the region. While the variation in the ALN agroclimatic conditions is large (Skjelvåg, 1998), this single site adequately represents the northernmost fringe of European agricultural production. The ALN zone may expect the greatest increase in the number of effective growing days; by 2050, the increase may match the present agroclimatic conditions of the ALS (Fig. 6b). Because of the high latitude of the ALN zone, the relative increase in the effective global radiation will be negligible. Overall, the agricultural potential of this zone is likely to improve; however, this is marginal in a European context due to the relatively small acreage of agricultural land in the zone (Table 1).

BOR

The growing conditions of the BOR region include special features that constrain yield formation (Peltonen-Sainio *et al.*, 2009b). The number of effective growing days under the present climate conditions is strikingly low (Table 5, Fig. 6a); the short growing season is further hampered by a relatively high risk of early-summer night frosts and a high proportion of dry days. Therefore, yields are typically far lower in the BOR zone than in other European regions (Peltonen-Sainio *et al.*, 2009a). Presently, only the late-spring sowing window is used, and most sowing occurs even beyond late spring. This is due to saturated soils that need to dry before sowing is possible with heavy machinery (Fig. 6j), low temperatures that slow germination, seedling establishment and early growth and a greater propensity for night frosts, which make early sowing economically risky (Peltonen-Sainio *et al.*, 2011). The overall low numbers of suitable days during the autumn sowing windows in the ALN, BOR and NEM zones are caused by ample precipitation and/or the early start of the winter season. The BOR zone has the lowest number of such days in late autumn (Table 5) and thus the present sowing window ranges from mid-August to mid-September (Peltonen-Sainio *et al.*, 2009b). Compared with the ALN zone, the increase in the number of effective growing days was projected to be much smaller as a consequence of the projected increase in the proportion of dry days in the BOR zone. Early-summer drought already severely limits yields in some years (Peltonen-Sainio *et al.*, 2009b; Rötter *et al.*, 2009). Of all the investigated zones, the MDS, PAN and BOR zones will have the fewest number of effective growing days by 2050 (Fig. 6a and b). It is likely that the agricultural potential of the BOR zone will remain comparatively low, even in the scenario of a 5 °C climate change.

NEM

Despite the fact that the NEM sites represent the upper limit of the NEM region, the accumulated sum of global radiation is quite similar across the entire NEM region (Skjelvåg, 1998). The low yields in this region are usually attributed to exceptional conditions that cause late maturity and/or pest infestations rather than low radiation input. The fraction of dry days varies across the region, which causes some variation in the suitability of both spring and autumn for sowing. The selected range of indices did not include winter temperature, which is known to be an important yield predictor for perennial and autumn-sown crops in the NEM, BOR and ALN areas (e.g. Samnordisk planteforedling, 1992; Blombäck *et al.*, 2009). Climate changes in the NEM region are likely to increase the crop-yield potential through improvements in the effective global radiation, effective number of growing days, date of last frost and proportions of sowing days (Fig. 6). Only the projected increases in the number of dry days during summer and interseasonal variability could potentially counteract the increases in crop-yield potential. Previous climate-change assessments for grass leys in Sweden have projected a considerably increased production in spring due to increased temperature, which enables an increased use of the high-intensity solar radiation in the spring (Torssell *et al.*, 2008). Using the present climate analogy, the NEM zone would achieve growing conditions that are close to those of present-day ALS, with a frequency of drought days and sowing conditions that are similar to those of the present-day ATN zone. These changes would probably support a shift from spring-sown to autumn-sown cereals (Eckersten *et al.*, 2008) and would enable the expansion of the cultivation of forage maize and similar crops. Under the + 5 °C scenario, the NEM area would achieve a Huglin index that is comparable to that observed in the present-day MDM area; the water deficit during dry years (based on a 20-year-return probability) would increase substantially.

ATN

The high yield potential of the north-western ATN zone, which is indicated by the relatively large effective global radiation in these areas, is confirmed by yield statistics for winter cereals (e.g. Schaller & Weigel, 2007). In terms of grassland productivity, Smit *et al.* (2008) claimed that the ATN zone has the highest production potential among all of the evaluated zones, followed by the ATC and LUS zones. This high productivity results from the relatively long summer days in combination with sufficient precipitation during the growing season, a long grain-filling phase due to moderate summer temperatures and recent increases in the thermal growing season (Chmielewski *et al.*, 2008). The high productivity is particularly evident in fruit-growing regions, e.g., near the Elbe estuary (Henniges *et al.*, 2007). Because of phenological shifts due to recent warming, resulting in earlier bud break and flowering, the risk for frost damage has remained unchanged for grapevines and fruits (Rochette *et al.*, 2004; Stock *et al.*, 2005; Chmielewski *et al.*, 2008; Henniges *et al.*, 2007; Eitzinger *et al.*, 2009) and it is likely to remain unchanged under the projected climate change. Increasing winter and summer temperatures may cause yield reductions in winter cereals (Kristensen *et al.*, 2011), but increasing summer drought may not necessarily reduce yields in this zone, where winter cereals develop deep roots and where current rainfall is generally not limiting. The increasing number of dry days in the June–August period (Fig. 6f) may reduce the yields of spring cereals (Wechsung *et al.*, 2008); however, this phenomenon might be partly compensated for by the earlier sowing of spring cereals (Olesen, 2005). Climate-change studies have generally shown an expansion of warm-season crops (e.g. maize, sunflower, soybean and grapevine) in this zone under climate change (Fronzek & Carter, 2007; Olesen *et al.*, 2007). This was confirmed by the projected changes in growing days, the Huglin index and date of last frost (Fig. 5).

ALS

Mountain chains act as climatic borders for the surrounding regions (e.g. delineating northern from southern EnZs in the Alpine mountain range) and contain a variety of climatic conditions due to strong topographical effects. This must be considered for the mountain regions in the ALS zone (e.g. the Alps and the Massif Central), resulting in a high spatial variability of climates. While there were only two stations selected in the ALS zone, they represent two of the six strata, wherein almost three-quarters of the agricultural area of the zone are located. It should be stressed that these stations represent low elevations that are relatively suitable for crop production. The potential productivities of both sites are at the higher end of all of the analyzed sites (Fig. 6) and the frequency of drought is very low, even during the summer months (Fig. 6e and f). The effect of climate change here was neutral to slightly positive, indicating slight increases in the variability and mean sum of effective radiation (Fig. 6a) and in the mean duration of effective growing days. The Huglin index of this region suggests that it might become suitable for grapevine cultivation; however, additional constraints in the ALS region, such as very low winter temperatures, poor soils and inaccessible terrain, will limit the cultivation of grapevines and other crops. There was a marked increase in projected days with water limitation (Fig. 5) during summer and in summer drought variability (Fig. 6f), threatening the productivity of permanent grasslands, which is one of the largest concerns in the eastern and southern parts of the Alps (Eitzinger *et al.*, 2009). Specifically, a mean global temperature increase of 5 °C would lead to a partial deterioration of productivity (Fig. 5). In the more humid ALS regions (north), an increased grassland biomass production potential can be expected. Similar effects have been projected for arable crop production in recent studies (e.g. Eitzinger *et al.*, 2009), with increasing crop-yield potential via the introduction of higher-yielding and later-ripening cultivars (e.g. maize) or new crops (e.g. soybeans and sunflower).

CON

The CON zone is the EnZ with the largest number of strata (12), the largest acreage of agricultural land (Table 1) and a high degree of variability between sites. The comparable potential productivity of the CON zone (expressed as effective global radiation and growing days) agrees well with the grassland productivity estimated by Smit *et al.* (2008). For the projected climate change, the overall mean for all CON sites (Figs 5 and 6) suggests no change, or even a decrease, in the effective global radiation sum and number of effective growing days. Whereas sites north of the Alps mostly showed increases in both indicators (see also Trnka *et al.*, 2010a), those in the southern parts of the CON zone demonstrated decreases of both indicators as a consequence of increased water stress. The projected values of the Huglin index suggest that viticulture will require changes in the cultivars grown (e.g. Stock *et al.*, 2005; Eitzinger *et al.*, 2009). The mean proportion of dry days from April to June did not change appreciably on average (Fig. 6e and f); however, there was a pronounced south-to-north gradient, with sharp increases in the proportion of dry days at southerly sites. The increase in the number of dry days from June to August represents a risk for rainfed agriculture across the present CON area, and this has already partly been reflected in the observed trends of drought since the 1940s–1950s (e.g. Dai *et al.*, 2004; van der Schrier *et al.*, 2006) as well as in national and regional studies (e.g. Wechsung *et al.*, 2008; Dubrovský *et al.*, 2009). Recent studies (e.g. Jacobeit *et al.*, 2009; Trnka *et al.*, 2009) have also pointed to the fact that changing frequencies of temperature and precipitation extremes are associated with changes in the frequency of particular circulation types. The early-spring sowing window should become longer (on average) and more stable (Figs 5 and 6i and k). These changes agree well with the shorter duration of snow cover, increasing spring temperatures and earlier start of the spring season (e.g. Chmielewski *et al.*, 2005; Brázdil *et al.*, 2009). Harvesting conditions in June (when the harvest of some crops will take place in the future) are not favorable, making the planning of suitable harvest times more challenging.

PAN

The climate of the PAN zone can be viewed as a variation of the continental climate (CON). The PAN zone primarily consists of flat regions and has warmer and drier summers and higher mean wind speeds compared with the neighboring CON region (e.g. Auer, 2004; Auer & Korus, 2005). This leads to typical steppe-like conditions and high reference evapotranspiration rates during summer (Müller, 1993). Agricultural production in the PAN region under the present climate is primarily restricted by a lack of water, particularly during summer (Table 5). The PAN region was projected to have the sharpest declines in effective global radiation as a consequence of large decreases in water availability (Figs 5 and 6a). The projected trend toward a warmer and drier climate is more pronounced here than in other zones (Fig. 3), and the severe consequences of climatic variability in parts of the PAN zone have been highlighted elsewhere (e.g. Seneviratne *et al.*, 2006). Crop production in the PAN is, to a large degree, dominated by arable production (especially that of maize, sunflower, winter wheat and spring durum wheat) and the results of crop-model-based studies in some countries have shown significant shortening of the growing season and a reduction in crop yields from increases in the frequency of summer drought and heat waves (Alexandrov & Hoogenboom, 2000). This shortening of the growing season could cause a significant loss in crop production and revenue in regions where no additional water sources are available (Eitzinger *et al.*, 2003; Alexandrov & Eitzinger, 2005). The PAN zone is also renowned for viticulture and high-quality white wines; however, the Huglin index in this region in 2050 is projected to become comparable to that of the present MDN zone.

ATC

The present agroclimatic conditions in the ATC zone result from its proximity to the sea, which reduces interseasonal variation in comparison to other zones; however, variability among stations at different altitudes and among seasons is still considerable, particularly for those indices that are associated with soil-moisture content. This can be explained by spatiotemporal differences in rainfall, wherein the oscillatory component in the rainfall series plays a key role (e.g. De Jongh *et al.*, 2006; Ntegeka & Willems, 2008). Frequent high-precipitation events during the late-spring sowing window are the primary cause of the lower number of suitable sowing days. The high number of effective growing days (Table 5 and Fig. 6b) and, to some extent, the effective global radiation levels (Fig. 6a) result in high yields of key field crops here compared with other European regions (e.g. Olesen *et al.*, 2011). The Huglin index of this region suggests only a marginal suitability for wine growing (e.g. Robinson, 2006); however, at some ATC sites, the conditions have been improving over the past few decades, as documented by Schultz (2000) and Eitzinger *et al.* (2009). The effective global radiation is not expected to change significantly, while the number of dry days is likely to increase (Fig. 6). Whereas Stock *et al.* (2005) demonstrated the tendency of a northward viticultural shift and an ascent to higher elevations, Schultz *et al.* (2005) have calculated a similar rate of increase in the Huglin index for Geisenheim/Rheingau (ATC-ATN) as found in our study. For the SRES-A1B scenario, projections have shown average shifts of the latest frost to earlier dates by 28 days for the period of 2071–2100 in Germany (Chmielewski *et al.*, 2008). The earlier start of the growing season results in a higher proportion of suitable sowing days in spring, as was also found by Rötter & van Diepen (1994). The tendency toward more drought stress (Figs 5 and 6e and f) was also reported by Gupta *et al.* (2006) for the Netherlands and by Holden *et al.* (2008) for Ireland.

LUS

Despite having the smallest total area of the zones considered in this study, the LUS zone has one of the largest proportions of agricultural land among all of the investigated zones. The large sum of effective global radiation and large number of effective growing days suggest a high potential productivity (Table 5), which is reflected in crop yields (Reidsma, 2007) and agrees with the findings of Smit *et al.* (2008) and Fisher *et al.* (2002) for grassland productivity. This region also contains well-known wine-producing regions, which have historically focused on the production of high-quality wines corresponding with favorable Huglin-index values (Fig. 6c). The risk of late frosts is low (Fig. 6d), as are the risks of drought occurrences during the early growing season and in the summer months, and there is a high proportion of days suitable for harvesting and sowing. The agroclimatic conditions of the LUS zone could potentially worsen through decreases in effective global radiation sums and effective growing days. Despite these changes, the levels of the last two indicators will remain comparatively high in the LUS region, accompanied by low drought risk in the early growing season. The change in the frequency of summer drought stress is quite important, as it will reach levels that are presently seen at PAN sites. The proportion of suitable harvest (Fig. 6g and h) and early sowing days (Fig. 6i) will improve, while the conditions during the late-spring and fall sowing windows will not change. Because the LUS zone hosts key wine-producing regions, an increase in the Huglin index (Fig. 6c) to levels near those presently observed in the MDN zone poses questions about the future of current terroirs (Seguin & Garcia de Cortazar, 2005).

MDM

Although only represented by one station in this study, the analysis of these results offers interesting information regarding potential impacts. Overall, the MDM zone is quite similar to the MDN zone (discussed below). Interestingly, the index that measures the change in last frost did not follow the pattern of MDN and MDS, as it retains the relatively large variability observed in the 1971–2000 period. The proportion of dry days for the period from April to June and June to August is expected to increase considerably for the MDM zone, as also predicted by Iglesias *et al.* (in press-a).

MDN

The results for the MDN zone reported herein are primarily based on sites in the Central Mediterranean and the Iberian Peninsula (Fig. 1). The current agroclimatic conditions at the analyzed sites suggest high potential productivity (Table 5), which is reflected in the very high grain maize and winter wheat yields in the MDN zone (Iglesias & Quiroga, 2007; Reidsma, 2007; Reidsma *et al.*, 2009; Iglesias *et al.*, in press-a) and in the high values of grassland productivity that have been estimated by various approaches (Fisher *et al.*, 2002; Smit *et al.*, 2008). However, grassland yields based on national statistics (Smit *et al.*, 2008) show that the MDN zone has a significantly lower productivity than the PAN and MDM zones, which may reflect frequent summer droughts (Fig. 6f) in combination with a lack of grassland irrigation (in contrast to arable crops). Harvest (Fig. 6g and h) as well as sowing suitability during early spring and fall were projected to reach very high levels. The late-spring sowing window will become unreliable as a result of spring droughts, which will make sowing or any other tilling operations problematic. Climate change is projected to decrease the sum of effective global radiation and increase the proportion of dry days during the early growing season together with an increase in interseasonal variability. An analysis of the 1955–2007 rainfall series confirms the current trend of reduced rainfall during spring and winter (Bartolini *et al.*, 2008). As a consequence, the proportion of drought days during summer (Fig. 6f) will vary less because almost all years will be affected by severe drought. Aside from drought, one of the perceived threats of climate change is the increasing probability of encountering lethal temperatures close to 40 °C. Crop-survival thresholds are still poorly understood and, thereby, there is a serious risk of future heat-wave-induced crop damage (e.g. Battisti & Naylor, 2009). Consequently, a significant increase in water demand for irrigation can be expected for this and the MDS region, not only for summer crops but also for winter crops, where in some regions the additional demand might not be met by the available water resources (Simota, 2009). The projected increase in temperature and decrease in precipitation in the MDN zone will also significantly decrease the soil-water content and water runoff to the Adriatic coast, resulting in negative consequences for the vegetation and agricultural production therein (Vučetić & Vučetić, 2000). The higher proportion of dry days during the period from April to June indicates a likely earlier onset of the wildfire season and an increased fire risk during summer (Vučetić *et al.*, 2006) as a consequence of longer summer dry spells (Vučetić, 1998). The impact of climate change on wine quality will be very high, as shown by Huglin indices (Fig. 6c) of around 3000, which are indices that are typically associated with the production of dessert wines (Grifoni *et al.*, 2006). An increasing temperature will reduce the occurrence of frost, but the real effect will have to be evaluated by considering the earlier onset of phenological phases and also the possible modification of air circulation (e.g. the possible intrusion of cold air from eastern Europe during March and April).

MDS

The potential rainfed productivity (Table 5) of this zone is limited by drought (Fig. 6e and f), not only during summer (Fig. 6f) but also in spring (Fig. 6e) and autumn, although this could be alleviated by irrigation (Reidsma *et al.*, 2009). A low productivity here was also reported by Smit *et al.* (2008) for grasslands and for winter wheat and maize by Reidsma (2007) and Reidsma *et al.* (2009). In terms of harvest suitability (Fig. 6g and h), June and July exhibited the most favorable conditions of all of the investigated zones;

however, the durations of the sowing windows (in particular those during early spring and autumn) were particularly low and variable (Fig. 6i and k), mostly as a consequence of increasingly dry soil conditions. Climate-change projections indicated decreases in potential productivity due to increases in the proportion of dry days and a decrease in the interannual variability of these parameters; however, this is hardly surprising given the character of the climate changes in these regions (Fig. 3). More specifically, sharp reductions in precipitation during summer and also in winter months (e.g. Zanis *et al.*, 2009) will likely result in increases in the number of consecutive dry days and heat-wave frequency (Beniston *et al.*, 2007) and the consequent decrease of soil-water content (Calanca *et al.*, 2006). Similarly to the MDN zone, the variability in the proportion of drought days during both evaluated windows (Fig. 6e and f) will decrease during summer and spring, which will further increase the risk of forest fires in the MDS region (Lavalle *et al.*, 2009). The likely impact of climate change on wine quality in the MDS zone is thought to be significant and negative (Fig. 6c). Finally, as in the MDN region, more effective irrigation methods, water management and policy in this region will be the main determinants of future crop distribution and productivity (Iglesias *et al.*, 2007, in press-b; Iglesias 2009; Katerji *et al.*, 2010).

Uncertainties in projected impacts

To date, the existing projections of European crop yields under climate change have been based mainly on the outputs of crop-growth models. While this strategy can be used to estimate the impact of climate change on crop yield, the simulation models usually do not capture crop management or environmental factors (e.g. extreme weather events) in their entirety. Moreover, crop-simulation studies are often limited with respect to the number of crops covered or the spatial coverage. The present study, which is based on selected indices, provides general, although limited, conceptions about fundamental agroclimatic conditions that govern crop-yield potentials and conditions for crop management across Europe. All assumptions and thresholds used in the study were based on published literature, and the sensitivity of our conclusions to the assumptions made was scrutinized by a sensitivity analysis (Table 2b), which showed that changing the thresholds used (e.g. ET_a/ET_r ratio) or modifying assumptions made (e.g. applying different reference surfaces for ET calculations) inevitably leads to variations in the absolute values of the indicators. However, the overall impact of the modified thresholds on the study conclusions was limited, i.e., the relative differences between the baseline conditions and those expected by 2030 and 2050 remained qualitatively the same.

Throughout most of the investigated zones, there were signs of deteriorating agroclimatic conditions and a need for adaptive measures to either increase soil-water availability (e.g. by irrigation or crop-management options) or crop drought resistance in the majority of the zones. While the impacts were demonstrated only for a selection of three GCMs, they represent a wide range of future projections quite well (Table 4).

Perspectives on European agriculture under climate change

Earlier European studies have emphasized that agriculture is expected to potentially benefit from climate change (e.g. Rötter & van Diepen, 1994; Olesen & Bindi, 2002); however, the responses of agricultural systems to changes in the frequency and severity of climatic extremes have rarely been considered in earlier assessments. Recent examples of damage in relation to floods, drought, hail and storms have revealed that the impacts of such extreme events are large (Kabat *et al.*, 2005; Gupta *et al.*, 2006). The present study confirms the substantial northward expansion of the thermal suitability of crop production in Europe under climate change found previously, e.g., by Fisher *et al.* (2002) and Olesen *et al.* (2007). The areas where conditions for rainfed crop production will be improved are restricted to the Northern regions (ALN, BOR and NEM), and partly in the ATN and the Alpine Mountains (ALS). This is the result of drier summers in much of central and southern Europe that will limit crop growth during summer unless irrigation is applied. This is not fully consistent with the results of Fischer *et al.* (2005), who predicted negative impacts on crop productivity only for Western Europe. The projected climate change does not seem to severely interfere with the possibilities for sowing and, to a lesser extent, harvesting, thus generally offering possibilities to adapt by changing sowing and harvesting dates in most European regions. The analysis shows that if the climate patterns evolve according to the assumptions and scenarios we used, some of the currently highly productive agricultural regions in Europe may be at risk of reductions in suitability for rainfed crop production. This is particularly the case for Western France and also parts of South-Eastern Europe (Hungary, Bulgaria, Romania, Serbia, etc.), where summers will become considerably hotter and drier, reducing crop yields and increasing yield variability. In these regions, winters will still be too cold to allow crop growth during winter. The Mediterranean zones will suffer from increases in dryness during spring and sharp declines in rainfed crop-production potential, posing the challenge of added irrigation capacity to irrigated Mediterranean areas, which must therefore become more efficient (Playan & Mateos, 2005). As shown by the Huglin-index values, the conditions for traditional crops such as grapevines will become more challenging, as also found by Jones *et al.* (2005) and Olesen *et al.* (2011).

Conclusions

Based on the evidence provided by our study, it can be concluded that rainfed agriculture in Europe may face higher climate-related risks; however, the analyzed agroclimatic indicators will likely remain at levels that permit acceptable yields in most years. Concurrently, our findings also suggest that the risk of extremely unfavorable years, resulting in poor economic returns, is likely to increase in many European zones. This projected increase in the variability of climatic suitability for crop production is particularly challenging for crop management and for agricultural policy, which aims to ensure stable food production and viable conditions for farmers. This therefore suggests that agricultural policy should encourage the adoption of both agroecological techniques and a diversification of production to increase crop resilience to climatic variability as well as the implementation of various insurance schemes (e.g. strategic grain stocks, farmer drought and flood insurances) and improvements in the efficiency of agricultural water use.

Because the costs of timely action may far outweigh the costs of inaction, an analysis of agrometeorological conditions in combination with agroclimatic projections under different climate-change scenarios across Europe offers the possibility of supporting early decision-making with regard to opportunities and risks. The analysis presented here should be conducted at regional and local levels to better reflect how specific localities may be affected.

Acknowledgements

This study was supported by the following projects: COST 734 (CLIVAGRI); DFFE 3304–FVFP–60651; Research plan No. MSM6215648905; KONTAKT OC187 and CzechGlobe – Centre for Global Climate Change Impacts Studies, Reg. No. CZ.1.05/1.1.00/02.0073.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1: List of the 86 sites used in the study.