Changing regional weather–crop yield relationships across Europe between 1901 and 2012

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ABSTRACT: Europe is, after Asia, the second largest producer of wheat in the world, and provides the largest share of barley. Wheat (and to a similar extent, barley) production in Europe increased by more than 6-fold during the 20th century. During the first half of the 20th century, this was driven by expanding the harvested area. This was followed, from the mid-20th century, by a massive increase in productivity that in many regions has stalled since 2000. However, it remains unclear what role climatic factors have played in these changes. Understanding the net impact of climatic trends over the past century would also aid in our understanding of the potential impact of future climate changes and in assessments of the potential for adaptation across Europe. In this study, we compiled information from several sources on winter wheat and spring barley yields and climatological data from 12 countries/regions covering the period from 1901–2012. The studied area includes the majority of climatic regions in which wheat and barley are grown (from central Italy to Finland). We hypothesized that changes in climatic conditions have led to measurable shifts in climate–yield relationships over the past 112 yr, and that presently grown wheat and barley show a more pronounced response to adverse weather conditions compared to crops from the early 20th century. The results confirm that climate–yield relationships have changed significantly over the period studied, and that in some regions, different predictors have had a greater effect on yields in recent times (between 1991 and 2012) than in previous decades. It is likely that changes in the climate–yield relationship at the local level might be more pronounced than those across the relatively large regions used in this study, as the latter represents aggregations of yields from various agroclimatic and pedoclimatic conditions that may show opposing trends.

KEY WORDS: Climatic trend · Weather–crop yield relationship · Wheat · Barley · Yield trend · Drought · Europe

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1. INTRODUCTION

Land management for food production is a fundamental human activity, supporting the lives of nearly everyone on this planet and providing livelihoods for a large part of the population. At present, more than 1.5 billion ha — approximately 12% of the world's land area — is used for crop production (FAO 2013). Wheat *Triticum aestivum* L., rice *Oryza sativa* L., maize *Zea mays* L., soybeans *Glycine max* (L.) Merr., barley *Hordeum vulgare* L. and sorghum *Sorghum bicolor* (L.) Moench. are the 6 most widely grown crops in the world. The production of these crops accounts for approximately 40% of global cropland area, 55% of non-meat calories and over 70% of animal feed (FAO 2006, 2013). Europe is a close second to Asia in global wheat production and provides the largest share of barley output. During the 20th century, wheat (and to a similar extent barley) production increased in some European regions by more than 6-fold (e.g. Slafer & Rawson 1994). This increase was initially due to an expansion in harvested area that occurred during the first half of the century, which was followed from the 1950s onwards by an increase of ca. 150% in global mean yield per unit land area (Slafer & Rawson 1996). For example, according to Slafer & Peltonen-Sainio (2001), the relative increase in countries such as Canada, Denmark and Finland between the 1950s and the 1990s was up to 83% for barley and 131% for wheat. In northern Europe, significant increases in the share of wheat grown over the cultivated area have been reported; for example, Denmark showed an 8-fold increase between 1971 and 1997 (Olesen et al. 2000). In recent years there has been a stagnation in cereal yields in most parts of Europe, which has been attributed (at least in part) to changes in agricultural policies, input intensities and changes in climatic patterns (Brisson et al. 2010, Finger 2010, Ray et al. 2012)

Limitations due to climatic conditions play an important role in the geographical distribution of crop species in Europe (Ewert et al. 2005, Elsgaard et al. 2012). In Mediterranean countries, cereal yields are limited by water availability, heat stress and the short duration of the grain filling period, while under the continental climate of eastern Europe (eastwards from central Poland), drier conditions and greater fluctuations in annual temperature limit the range of crops that can be grown. The most productive regions in Europe in terms of climate and soils are located in the 'North European lowland plains', which were shaped by the most recent ice age, have a largely Atlantic temperate climate and stretch from south-east England through France, Benelux and Germany and into Poland. There are additional lowland regions (e.g. the Hungarian Plain) that also have quite favorable conditions for crops. From a global perspective, food supply security in Europe is likely to be less influenced by climate change than it may be in other regions because of technologically sophisticated agricultural practices (Brown & Funk 2008), but climate-induced uncertainty (i.e. substantial fluctuations) in food production may result from elevated temperatures and associated changes in the frequency of adverse events in the future (e.g. Trnka et al. 2015). This agrees with the views of Lobell & Burke (2008), and more recently with those of Porter et al. (2014), who proposed that research should focus on crop responses to elevated temperatures to assist in designing cropping systems that are resilient to the effects of global warming. While production for all crops has increased substantially since 1961, temperature and precipitation, spatially weighted for each crop, have also exhibited significant trends (Lobell & Field 2007). For wheat, maize and barley, there is a clearly negative response of global yields to increased temperatures (Porter et al. 2014). Based on their sensitivity and the observed climatic trends, it has been estimated that warming since 1981 has resulted in an annual combined loss of these 3 crops representing approximately 40 Mt (megatons), which represents \$5 billion yr^{-1} as of 2002 prices (Lobell & Field 2007).

Many studies have considered the effects of past climate variability on agriculture (e.g. Calderini & Slafer 1998, Lobell & Field 2007, Finger 2010, Peltonen-Sainio et al. 2010, Lobell et al. 2011, Olesen et al. 2011). However, they have mainly focused on the most recent decades, for which yield and climatological data are relatively easy to obtain. They also relied only on national statistics due to the better availability of long-term datasets (e.g. Calderini & Slafer 1998). Therefore, such studies generally do not consider crop–climate relationships prior to the recent warming that has occurred during the last 3 decades of the 20th century. It is likely that warming (a global increase of 0.74°C between 1906–2005, according to Solomon et al. 2007; or 0.85°C between 1880–2012, according to Stocker et al. 2013) has improved the agroclimatic conditions in many regions of Europe, and hence increased the yields of many crops, but it has also led to less favorable conditions and yield reductions in other regions (e.g. Trnka et al. 2011). It is also possible that such differences would more likely be found within relatively small regions than at a national level, which usually represent the aggregation of yields from various agrocli-

matic and pedoclimatic conditions, as Trnka et al. (2012) showed in comparing the late 19th century and contemporary district/county level yields in central Europe.

An understanding of the net global impact of climatic trends over the past century would aid in our understanding and quantitative assessment of the potential impact of future climate changes, and in determining future agricultural adaptive potentials. The major challenge in setting up 'historical' studies in Europe stems from the extensive changes that have occurred with respect to borders (both national and regional), state systems and inventory methodologies, which in some regions seriously affect the availability of yield data and to some extent that of climatological data. In addition, socio-economic crises, often caused or followed by wars, have had severe impacts on agricultural production and the productivity of crops. This study compiled several sources of data for 12 European countries/regions (see Fig. 1), aiming to collect the most complete datasets for the 1901−2012 period.

2. DATA AND METHODS

The regions studied are located along a north−south transect of Europe and represent the area between 41° 14′−71° 11′ N and 2° 33′−31° 35′ E (see Fig. 1). The regions cover 1 620 847 km^2 of land (representing 37 % of the present area of the EU), 205 866 km^2 of which is arable, corresponding to 19 % of the arable land in the EU (see Table 1). Regions were selected according to the following criteria: (1) comparable acreage of arable land (8400−37 200 km^2); (2) targeted crops (barley and wheat) are significant crops in terms of acreage, and are the most common cereal crops in the area; (3) little or no change in the administrative borders of the region during the 1901−2012 period; (4) availability of yield data.

The final selection included 10 countries and 2 regions at the sub-national level (Lower Saxony and Tuscany) (see Fig. 1, Table 1) that represent a broad range of climatic patterns, changing from warm and dry Mediterranean conditions (Tuscany, Croatia) or those of the Black Sea area (Bulgaria) through central Europe (Austria, Czech Republic) to the northern margins of agriculture in Europe (Norway, Finland). Some of the regions belong to traditional farming areas with high yields of both crops (The Netherlands, Belgium, Lower Saxony, Denmark), but other regions are in areas that are close to the northern (Norway, Finland) or southern (Tuscany, Bulgaria,

Croatia) extents of the growing areas for both crops in Europe. The final selection also included 3 'eastern' European countries, where production and productivity were enhanced through different mechanisms (former communist countries) than those used in their western counterparts between ~1945 and 1990. The Czech Republic, Croatia and Bulgaria then experienced a period of transition to a free-market economy, which was achieved on joining the EU in 2000.

The monthly minimum, mean and maximum values for air temperature, precipitation, number of precipitation days and drought severity, expressed in terms of the Palmer Z-index and Palmer Drought Severity Index (Palmer 1965), were used as predictors of inter-annual yield variability (for a more detailed description of the Palmer Z-index, see Trnka et al. 2009). The monthly climatological data for each region were based on the CRU TS 3.21 dataset (released on 16 July 2013 at http://badc.nerc.ac.uk/browse/badc/cru/data/cru_ts [note that the site requires that one resgisters before accessing the data]; for more details see Mitchell & Jones 2005, Harris et al. 2014). Gridded data with a resolution of 0.5 × 0.5 degrees were based on mean monthly temperatures provided by >4000 weather stations around the world. Using this gridded data, a series of each climate variable was calculated for each region, using the proportion of arable land within the given grid and region as a weighting factor. For individual periods, the proportion of arable land within each grid was derived as the mean value for the given period using Global Cropland Data (1700−2007), which provides revised data described by Ramankutty & Foley (1999) and is available at www.earthstat.org/data-download/. The final series of climate variables are provided in Supplement 1 at www.int-res.com/articles/suppl/c070p195_supp/.

Originally, 6 crops were considered for analysis: wheat, barley, rye *Secale cereale* L., oat *Avena sativa*, potato *Solanum tuberosum* L. and sugar beet *Beta vulgaris* var. *altissima*. However, only wheat (particularly winter wheat) and barley (particularly spring barley) had sufficiently large acreage and yield data available in all regions during the periods analyzed. Therefore, they were selected for analysis in this study (see Supplement 2 at www.int-res.com/articles/suppl/c070p195_supp/). The bulk of the data were provided by individual co-authors of the study from regionally available data, and these were confirmed — when possible — with supranational databases (particularly http://faostat3.fao.org/home/E and http://ec.europa.eu/eurostat/data/database). The final

dataset used in the analysis is given in Supplement 2. An extensive search of the relevant archives did not provide any further data for other periods beyond those analyzed in this paper. Although some of the European regions in this study went through significant changes in their borders and even their statehoods (e.g. Czech Republic, Austria or Croatia) during the period examined, the impact of these changes on the methodology of data collection were relatively small. In preparing the analysis, we aimed to select areas where yield data were thought to be available and where changes in regional borders were relatively minor during the 20th century. However, in some cases data could not be obtained. For example, despite prolonged efforts, no yield data in the 1901–1920 period could be found for Tuscany or the Czech Republic. In addition, the war years from 1941–1945 were characterized by a higher number of missing data. Based on the analysis of break-points in the yield series, we defined 3 periods for which relationships between climatic variables and the yields of spring barley and winter wheat were studied: 1901–1950, 1951–1990 and 1991–2012.

Instead of using the annual means for each climatic variable, we defined a key period of the growing season during which barley and wheat are most sensitive to climatic variables. For both crops and the majority of the regions, we found that climatic patterns during April–June played a key role in determining yield, which is in agreement with results of Hlavinka et al. (2009) and Gobin (2012), as well as with the local knowledge of the authors of this study. As there was concern that conditions during July could significantly influence crop yields in cooler European regions (Kristensen et al. 2011), the initial analyses were made for all potential combinations; i.e. all months, all seasons and several month combinations (in total, 24 different time windows). The overall April–June period showed the most stable results with April–July or May–July being notably worse in the central and southern part of the evaluated region. The added value of using the April–July or May–July or June–July period for regions in the north of the regions compared to April–June was very limited and led to the same results. Therefore, the April–June period was selected to decrease the number of assumptions. However, for a consequent analysis (which is planned for those countries where the Nomenclature of Territorial Units for Statistics [NUTS 4] data will be available, at least in past decades) the effort will likely utilize a varying time window as one approach. To evaluate links between the yield series and climate, we always analyzed the relationships between deviations in the climate variables and the crop yields. We used 3 methods, which were based on (1) first order differences, (2) deviations from local means and (3) deviations from the trend curve.

(1) Approaches based on a first order difference series for yield and climatic variables (i.e. the difference from one year to the next) have been applied in a number of studies (e.g. Lobell & Field 2007, Trnka et al. 2012). We transformed the first order differences of climatic variables and yields (yield estimates) into a z-score series using the mean and standard deviation of the period analyzed. We then performed multiple linear regressions, with the first order differences in yield (Yield) as the response variable and the first order differences in mean temperature (Tavg), maximum temperature (Tmax), minimum temperature (Tmin), precipitation totals (PREC), number of frost days (FRS), number of precipitation days (WetD), water vapor pressure deficit (VAP), potential evapotranspiration (PET), Palmer Z-index (ZIND) and Palmer Drought Severity Index (PDSI) as predictors.

(2) We also calculated deviations from the local mean yield (calculated as the difference from the 6 closest values in the database for the given region) which were transferred into z-scores, and z-scores of the particular climatic variable.

(3) When applying the approach based on the deviation from the trend curve, we used the difference from the trend line, or the 2nd, 3rd or 4th order polynomial that fit to the line that best described the yield development. The difference was again transformed into z-scores and correlated with climatic variables.

As the results of all 3 approaches were not significantly different, we used the first order differences method as this is the simplest and requires a lower number of assumptions than the other two. In the preparation phase, other variables were also considered e.g. standardized precipitation index (SPI), standardized precipitation evapotranspiration index (SPEI) or amount of snow cover. However, in case of SPI and SPEI the results were similar to PREC and ZIND/ PDSI respectively, while monthly data based snow cover estimates did not correspond with observed daily data. Therefore we focused on the 10 straightforward climate predictors defined above.

The detrending method was used, as it is designed to minimize the influence of slowly changing factors, such as crop management techniques and farm technology, and allows for the examination of the season-to-season (or season to long-term yield level) responses of yields to changes in the selected climatic variables. It was assumed that year-to-year manage-

ment changes were not correlated with the climatic variables for the given year, but rather resulted from the experience gained in the previous years as a continuous process of learning from past mistakes throughout the time period analyzed in the paper. In addition, the division of the analysis period around 2 break-points, when yearly rate of yield changed markedly, allowed comparability over the whole analyzed period.

We also assumed that errors in a yield database were independent of climatic parameters. There were very significant shifts in the type of cereals being grown; rye was replaced by wheat, and oats by barley (e.g. Olesen et al. 2000). However, wheat and barley were among the 10 most commonly grown crops in most of the European regions throughout the study period. Therefore, they were assumed to always be present at sufficient acreage across the region of interest.

3. RESULTS

3.1. Changing production levels

The selected regions represent a climate gradient for the production of spring barley and winter wheat (Table 1, Fig. 1). They include regions with rather low annual and April–June temperatures that have either relatively dry (Finland or Sweden) or wet (Norway) spring and early summer conditions. Furthermore, the study included the highly productive areas of Lower Saxony, Denmark, Belgium and The Netherlands, as well as some regions with significant water limitations, such as in the Czech Republic, Austria and those more to the south in Tuscany and Bulgaria. As shown in Fig. 1d,e, climatic conditions between the periods of 1921–1940 and 1991–2010 changed considerably. All regions showed a significant increase in annual mean temperatures, which in some regions was even more pronounced from April–June. Annual precipitation totals either increased or remained the same, with the exception of Tuscany, which had a decrease in precipitation. The April–June precipitation levels markedly decreased in Bulgaria, Tuscany and Croatia and were notably increased in Norway, Sweden and Belgium. Fig. 1 shows that the 12 regions include not only the main crop producing areas but also regions with relatively low proportions of wheat and barley. The selected areas also represent a range of the environmental zones defined by Metzger et al. (2005) (Fig. 1a). In these regions, wheat and barley were

Table 1. Land-use, soil conditions and crop productivity in the 12 European countries/regions included in this study. Environmental zones follow those in Fig. 1a

	Finland (FI)	Norway (NO)	Sweden (SE)	Denmark (DE)	Lower Saxony (LS)	The Netherlands (NL)	Belgium (BE)	Czech Republic (CZ)	Austria (AT)	Tuscany (IT)	Croatia (CR)	Bulgaria (BG)
Total area (10^3 km²)	333.7	322.4	449.1	43.3	47.7	37.4	31.0	78.9	83.9	57.9	56.5	110.9
Total area of arable land (10^3 km²)	30.0	16.1	31.4	27.7	18.6	10.1	8.4	32.3	15.1	12.2	9.6	28.8
Proportion of arable land (%)	9	5	7	64	39	27	27	41	18	21	17	26
Mean altitude of arable land (m a.s.l.)	73	155	71	32	61	3	95	372	316	136	102	228
Mean annual temperature (°C) (arable land)												
1901–1950/	3.2	3.3	5.2	7.6	8.6	8.7	9.3	7.5	7.1	11.8	10.6	10.8
1951–1990/	3.2	3.3	5.2	7.7	8.5	8.6	9.3	7.8	7.4	11.9	10.6	10.9
1991–2012	4.1	4.0	5.9	8.5	9.4	9.5	10.2	8.6	8.4	12.5	11.6	11.4
Mean annual precipitation (mm) (arable land)												
1901–1950/	522	1039	548	675	667	672	763	672	985	730	909	572
1951–1990/	535	1083	566	707	686	705	794	648	948	744	871	588
1991–2012	563	1153	622	723	709	746	825	655	966	711	875	601
Soil water-holding capacity (mm m⁻¹)	80–130	100–140	140–190	100–140	100–140	140–190	>190	140–190	140–190	140–190	140–190	140–190
Environmental zones	BOR, NEM	BOR, NEM	NEM, CON	ATN, CON	ATN, CON	ATC, ATN	ATC, CON	CON, PAN	PAN, CON	MDN, MDM	PAN, MDM	PAN, MDN
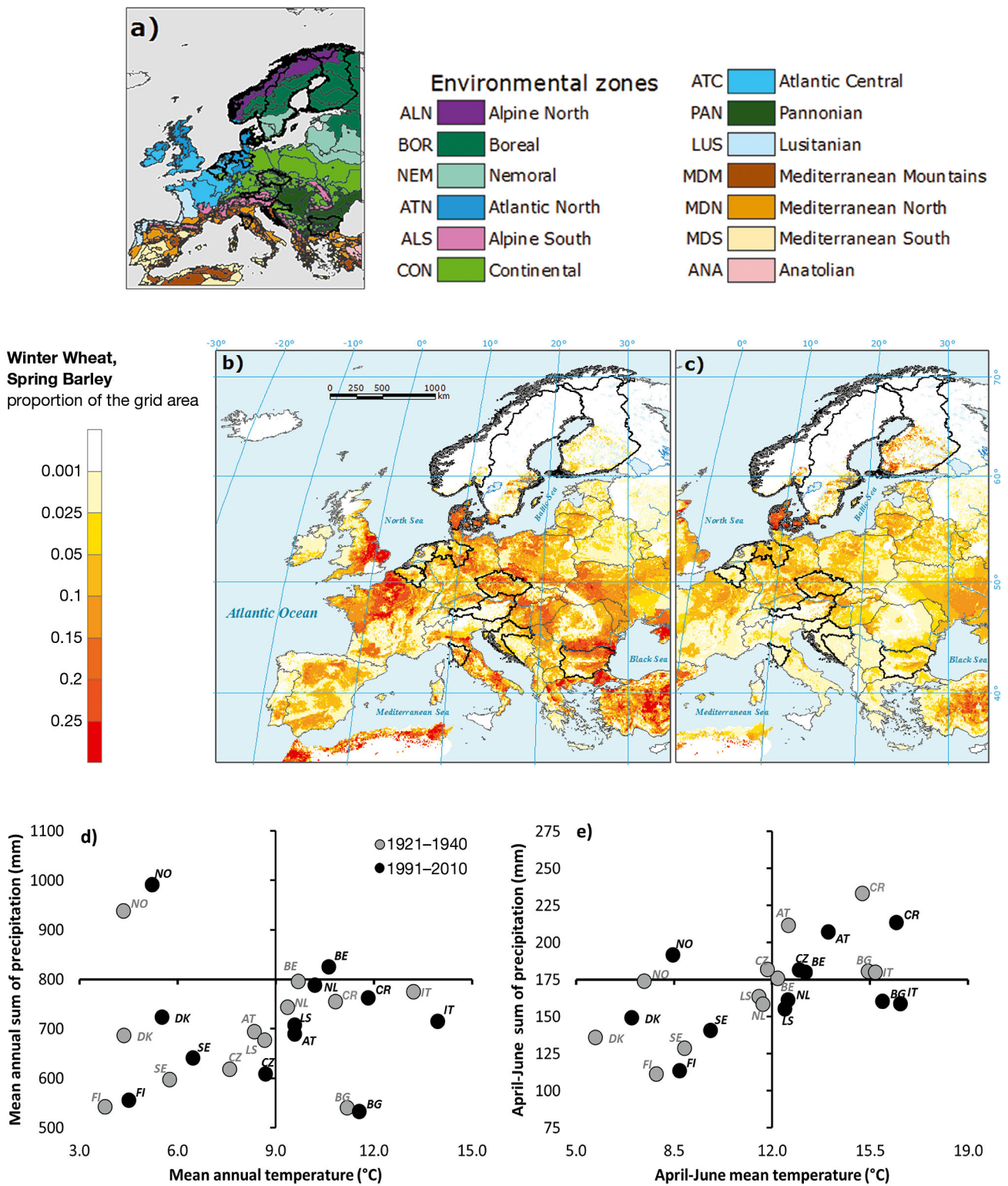
Fig. 1. (a) Main environmental zones in Europe, based on Metzger et al. (2005); (b) wheat and (c) barley growing areas in Europe, based on Monfreda et al. (2008), and the locations of the 12 countries/regions assessed in the study (thick borders). Mean (d) annual and (e) April–June temperature and precipitation for the 12 countries/regions (for abbreviations see Table 1) over the periods 1921–1940 and 1991–2010. Climatological data were weighted according to the proportion of arable land in each grid of the region

mostly grown in the Atlantic North, Atlantic Central, Continental, Pannonian and Mediterranean (northern and mountainous regions) zones, but Nemoral and Boreal zones are also represented.

Table 1 and Supplement 2 show that the 1951–1990 and 1991–2012 periods are fairly well covered by yield data (with some exceptions for the 1950s in Sweden, Norway, Bulgaria and Austria). The 1901–1950 period has the worst coverage (see also Supplement 2), but with exception of Tuscany, each region is represented by at least 25 yr of yield data. In the 1915–1919 and 1939–1948 periods, yields were affected by World Wars I and II and their aftermath. Especially in these years, data were missing for some countries (e.g. Austria, Czech Republic or Croatia) as yields were considered secret information. However,

we included all available data even from these periods, because farmers would have strived to maximize production even during periods of war. Potentially disruptive events and major changes in the socio-economic structure of the society that could affect yield levels and overall agricultural practices are listed in Table 2 for each country. Rain was the source of water for virtually all of the cereal production during all periods analyzed.

Crop compositions and land allocation were comparable and did not differ by more than 1/3 across all regions (Fig. 2e,f). Fig. 2 (based on Ramankutty & Foley 1999) shows considerable changes in the proportion of arable land across Europe in the 20th century. However, one of methodological aims of this study was to analyze primarily those regions where
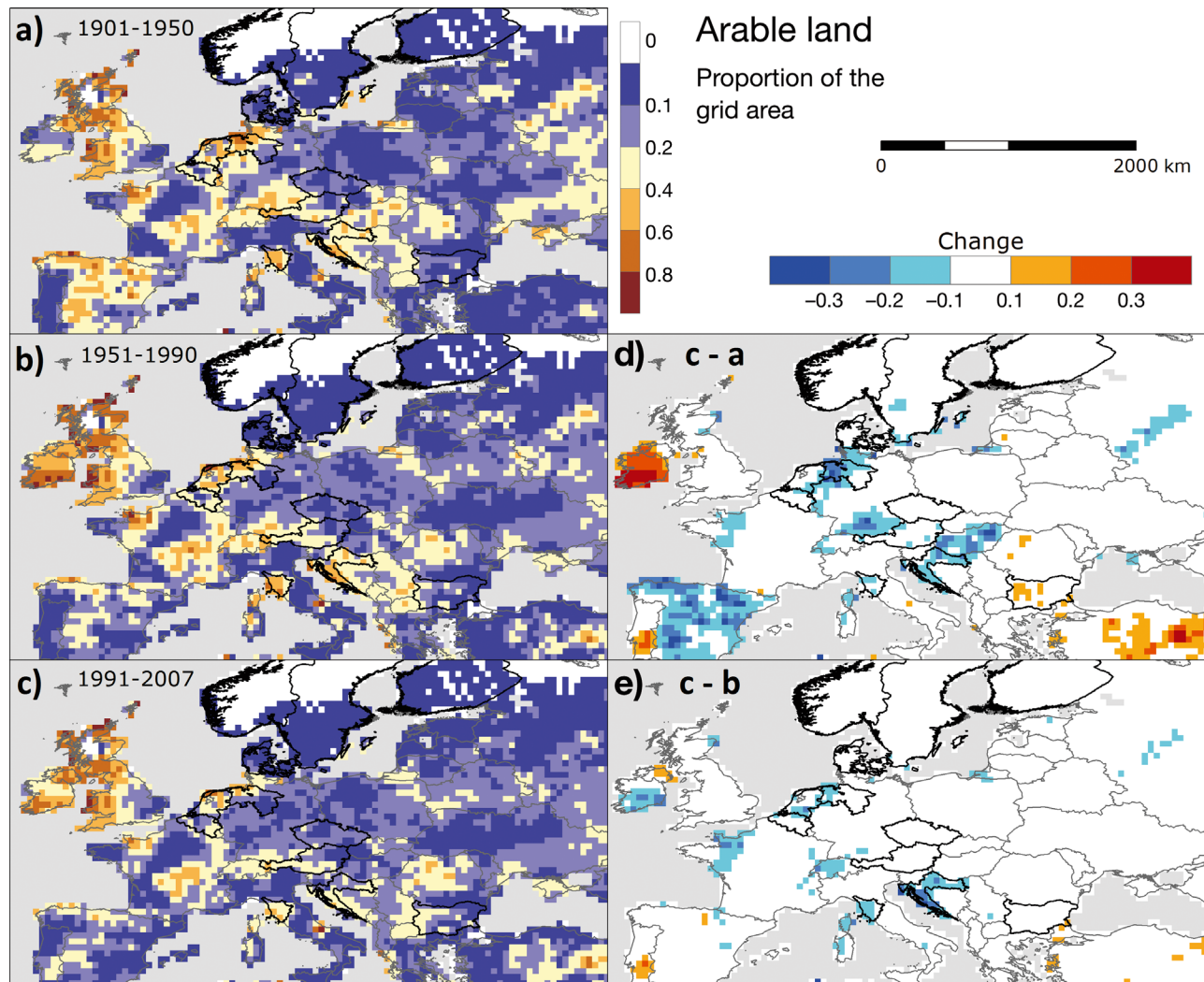

Fig. 2. Proportion of arable land based on the updated Ramankutty & Foley (1999) study for the periods (a) 1901–1950, (b) 1951–1990 and (c) 1991–2007, and the differences between the periods (d) 1991–2007 and 1901–1950 and (e) 1991–2007 and 1951–1990. The 12 countries/regions considered in the study are indicated by thick borders

Table 2. Key factors influencing productivity in the 12 European countries/regions studied (ordered from north to south). See Table 1 for country/region abbreviations

Country/region	1901–1950	1951–1990	1991–2012
All	Introduction of mineral fertilizers and a period of technological development prior to WWI	Large-scale use of fertilizers, pesticides, and later, growth regulators, machinery and new types of cultivars	Efforts to reduce the environmental impacts of agricultural production. Farmers, due to subsidy systems, were less motivated to maximize yields
FI	Traditional crop rotations prevailed with little mineral fertilizer input and mechanization limited	In the 1950s and early 1960s, Finland suffered from a lack of capital for investments due to reparation payments to Russia in the aftermath of the 'winter war' and WWII	Finland joins the European Union in 1995 and adheres to more stringent environmental regulations. Drastic cereal price decreases and decreases in N and especially P fertilizer rates due to Agro-Environmental Programme subsidies led to extensification and an increase in cereal crop area (to mainly less-favorable land)
NO	A regionalization of agricultural production was initiated and completed. Cereal production was located mainly in southeast and central Norway. Milk and meat production was mainly located in areas less climatically favorable for cereal production. Mechanization was boosted and the application of fertilizers and pesticides increased continuously until environmental issues required more attention	A regionalization of agricultural production was initiated and completed. Cereal production was located mainly in southeast and central Norway. Milk and meat production was mainly located in areas less climatically favorable for cereal production. Mechanization was boosted and the application of fertilizers and pesticides increased continuously until environmental issues required more attention	Norway did not join the European Union and agriculture is not a part of the (EEA) agreement with the EU on economic affairs. However, according to the agreement, several EU regulations were also applied in Norway
SE	Wheat started to replacing rye. Fertilization rates slowly increased	Mechanization of agriculture reduced the number of horses and cows. Leys were increasingly replaced by barley for pig production. Cereal monocultures became more common. Increased fertilization rates	Agriculture became market oriented and economy regulated cropping. Subsidies were based on area. Larger farms developed. Fertilization rates were reduced and yields stagnated
DK	Increasing exports of cereals. Dairy and meat organized through cooperatives stimulated productivity	Mechanization combined with the increased use of fertilizers and pesticides increased productivity, and this was linked to the increased specialization of production systems	Increased environmental regulations to reduce pollution from nitrogen (in particular nitrate leaching) and pesticide use impacted crop management and limited increases in productivity
LS	Earlier harvests before the introduction of combine harvesters. Nitrogen limitation, because mineral N was not yet used extensively. Therefore, wheat was mainly cultivated on good loess soils in the south	Strong increase in wheat (4-fold) and barley (6-fold) area, partly as extensions on former grasslands, which was drastically reduced	Reduction of nitrogen surplus, further reduction of grassland to 1/5 of the 1st period, reduction of barley area by 50% (mainly replaced by silage maize), and a further increase in wheat area by another 40% relative to 1990
NL	A somewhat delayed but then rapidly recovering and expanding agriculture along with land reclamation (polders)	Heavy investments in agricultural research and technology on all levels resulting in large increases in agricultural production. An awareness of excess nutrients developed towards the end of the period	Emphasis on resource use optimization
BE	More than 1/3 of the population worked in agriculture and related sectors, and more than 2/3 of the territory was farmland	Growing industrialization encouraged the specialization and mechanization of agriculture and agro-industries. From the 1970s, a clear trend existed towards fewer and larger farms	Increasing agricultural productivity while reducing environmental impacts was key. Increased exploitation of agricultural and horticultural expertise in the retail market and in the international niche markets

Table 2 (continued)

Country/region	1901–1950	1951–1990	1991–2012
CZ	Following land-reforms in 1920, large scale farms were redistributed, and institutional support of breeding and crop improvement occured. Post-WWII recovery was relatively slow and was affected by 1947 drought	Complete land re-distribution and establishment of ever-larger cooperatives. From the mid-1970s, industry-like agriculture farms with ever increasing size	Shift in priority from the highest yield to the highest profit and a general reduction in the application rate of fertilizers and pesticides. The effects of EU agricultural policies from the mid-1990s are apparent
AT	Increasing use of mineral fertilizers and farm technologies (machinery), which was slowed down significantly by 2 world wars and the fact that practices were based on very small farm units in most regions. Crop breeding improvements and the introduction of new crops, such as maize, occured	Strong improvements in applied farm technologies, significantly replacing man-powered machinery in all farming sectors. Strong improvements in crop breeding success and crop management methods, such as soil cultivation techniques, pest and disease control. Better demand-driven crop fertilizing, improved extension services and education resources and options for farmers. Significant structural changes in farms to larger farm units and farm-based specialization to one production type (i.e. giving up cattle and milk production in arable regions, focusing on different crop production only or in combination with meat production)	Further ongoing strong structural changes in farms leading to larger farm units. Strong dependence of farm productivity and economic survival, especially in disadvantaged regions (i.e. Alpine region), on second income options and subsidies. Further improvements in the implementation of sophisticated, new and more resource-efficient farming technologies and methods in all farming sectors. Significant loss of agricultural land due to the demand for area for urbanization, infrastructure and reforestation (Alpine region). Increasing share of farms and agricultural land under ecological production as an option for keeping smaller, family-farm based production
CR	Traditional agricultural production on small family farms where conventional tillage and soil fertilization using manure dominated	After a failed collectivization, state agricultural enterprises were established on 10% of the agricultural land, and the rest of the agricultural land remained privately owned. Agriculture within the state-owned agricultural enterprises was intensified and focused on high yields at the expense of ecological and economic efficiency	Family farms and agricultural enterprises were the main drivers of agricultural production. Transition to a market economy. Subsidies were introduced. Orientation towards organic and integrated agriculture production
IT	Crop rotation was widely adopted, no mineral fertilization was adopted, and a varietal selection of wheat grown had a very strong impact	Introduction of mechanization and the adoption of intensive agricultural practices. Crop rotations were abandoned in favor of increased mineral fertilization	More attention to grain quality in addition to high yields, sowing density increased for controlling tillering ('one seed, one ear'), and crop rotations were re-introduced in agricultural practices.
BG	Agricultural development through extensive growth. Productivity gains only played a marginal role to output increases. No significant growth of yields before 1940	Among the countries of Eastern Europe, Bulgaria was the first to complete collectivization, had the most collectivized agriculture, and experienced the most rapid rate of growth of agricultural production since the end of World War II. Emphasis on high-value products and significant improvement of the relatively low level of agricultural production by increasing the supply of fertilizer, machinery, other investments, and improved plant varieties. Extensive development of irrigation	In 1990, the total irrigated land was 25% of the arable land. During transition, the amount of water used for irrigation sharply declined post-1990. Wheat and barley replaced more water-intensive crops, including vegetables, rice and maize. Irrigation systems and other infrastructure elements were built to serve large production units during socialism and did not meet the needs of the huge number of small-scale landowners that emerged following the land restitution process

the changes in the proportion of arable land have been less pronounced. Fig. 2e,f shows that in most regions, the area of arable land has not changed considerably, with exception of Belgium, Croatia and Tuscany. Comparing 1991–2012 with 1901–1950, the decreases in arable land were between 10 and 20% in some areas within these 3 regions. These areas have been mainly converted to permanent grassland or, to a lesser extent, to forest. From 1991–2012, the proportion of arable land did not change dramatically in any of the evaluated regions when compared to the proportion in 1951–1990 (Fig. 2f). Fig. 2 allows for the analysis of changes in the weights assigned to the individual grids that were used to calculate the agroclimatic conditions within individual countries. These changes were rather small and were thus kept constant over the whole study period, with the distribution of the year 2000 being used. However, some changes were not covered by Ramankutty & Foley (1999), as Table 2 shows for Lower Saxony.

3.2. Yield trends

Fig. 3 shows that the series of barley and wheat yields exhibited slow rates of increase until approximately the late 1940s, at which point the annual yield increased much faster and reached a plateau that has lasted since the 1990s.

The yield variability (when normalized by the mean yield level) did not differ significantly between periods. When data from all regions were pooled together there was a good agreement on the 'break-points' in the wheat and barley series. The period of slower annual yield growth ended in 1952 for barley and 2 yr later for wheat. The following period of rapid annual yield growth ended in 1989 and 1990 for wheat and barley, respectively. There are obvious and significant differences between individual regions with some having only one distinctive 'break-point' around early 1950s. However, a break-point analysis was used to select the following 3 distinctive periods for the subsequent analysis: 1901–1950, characterized by slower changes in annual yield; 1951–1990, showing rapid increase in annual yield; and 1991–2012, with a recent slow-down in changes in annual yield.

The large differences between the 3 selected periods are well depicted in Fig. 3a,b. In the most recent period (1991–2012), we can distinguish 3 groups of regions. (1) The 3 Nordic countries (Finland, Norway, Sweden) had generally lower yields than other regions and smaller yield increments relative to those from the 1951–1990 period, and even relative to those from 1901–1950 period. (2) Comparable results were found for the central and southern European regions (Czech Republic, Austria, Croatia, Tuscany, Bulgaria), where yields of barley were similar to those of the Nordic countries, but wheat yields were markedly higher. This partly follows from differences in soil conditions, i.e. the often sandy (relatively poor in nitrogen and phosphorous) or relatively shallow or water-logged soil profiles in some Nordic countries compared to the generally deeper and more fertile soils in central (Austria and Czech Republic) and southern (Tuscany, Bulgaria) Europe. Wheat is primarily grown on better soils due to its generally higher yields. (3) The third group is represented by Denmark, Lower Saxony, The Netherlands and Belgium, where wheat yields in particular were much higher than in the other regions and the yield differences between the 1991–2012 and 1951–1990 periods were the greatest, primarily due to favorable climatic conditions. In addition, apart from climatic factors, high yields could be to some extent attributed to (i) surplus manure stemming from high livestock densities, (ii) relative land scarcity due to high population pressures encouraging higher and more cost-efficient investments in farm infrastructure (particularly in Belgium and The Netherlands), (iii) past investment into agricultural research and development and (iv) more homogeneous terrain in the northwestern/central countries than in the Nordic ones or those in the central/southern regions.

3.3. Climatic effects on wheat yields

3.3.1. Individual climatic parameters

Only negative associations were established between first order differences of annual wheat yields and selected climatic parameters (Table 3). In the case of minimum temperatures and water vapor pressure deficits there was a significant (yet weak) relationship across all 3 periods. Yields across all regions and over the whole period responded significantly to all parameters, with the exception of potential evapotranspiration — which is not surprising as actual evapotranspiration would be a better indicator of water availability. Overall, inter-annual climatic variations explained only a small fraction of the wheat yield variations when they were considered separately. At the level of the individual regions, individual climatic parameters tended to explain a greater proportion of the year-to-year yield variations. Total precipitation explained up to 60% of the year-to-year yield vari-
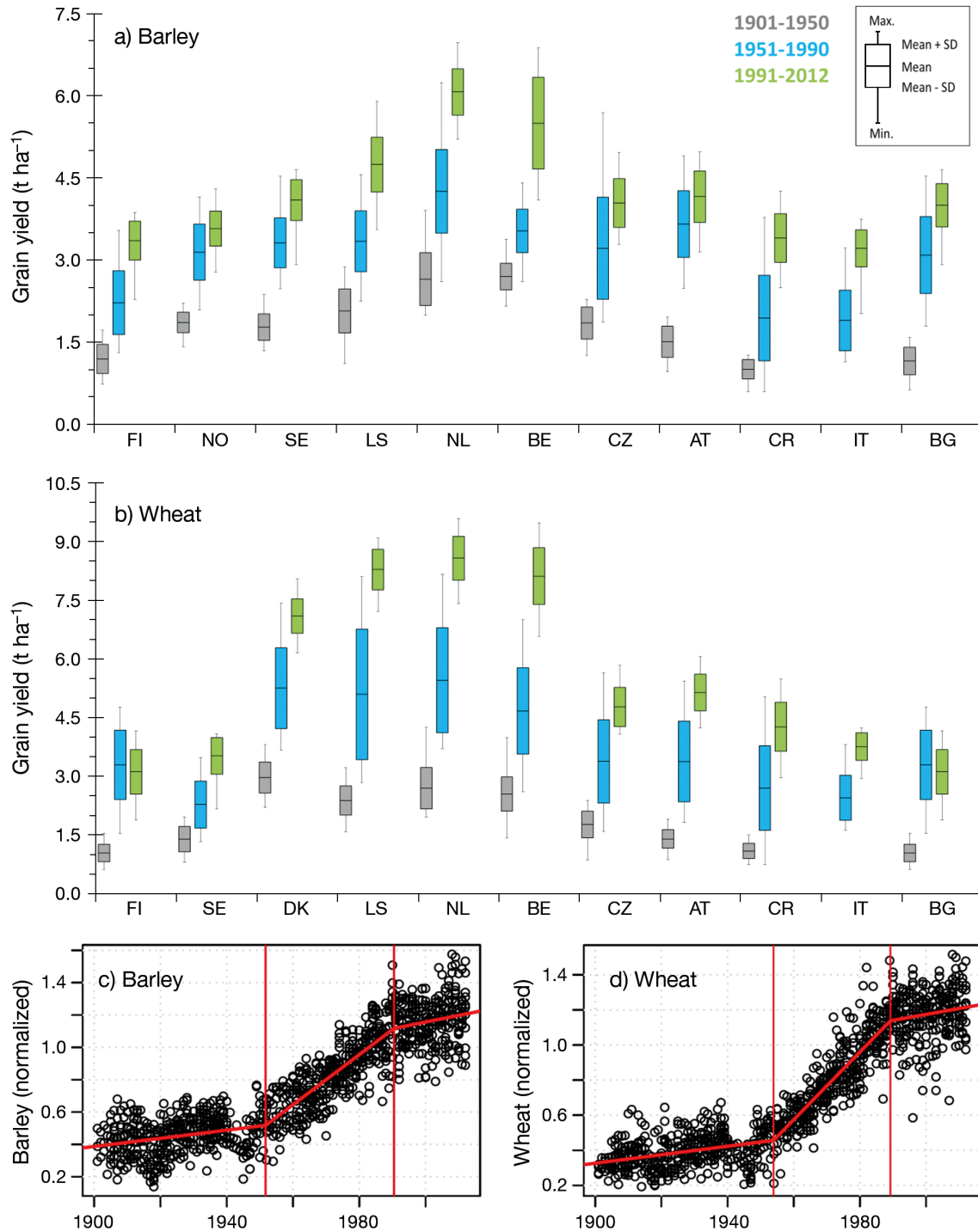
Fig. 3. Distribution of (a) barley and (b) wheat yields expressed as box-plots for the countries/regions included in the study for the 1901–1950, 1951–1990 and 1991–2012 periods. (c,d) Inter-annual variability of normalized yields for (c) barley and (d) wheat in all countries/regions with 'break' lines

ability in Belgium, The Netherlands and Lower Saxony, and a similar response was found across all 3 periods studied. On the other hand, temperature-related characteristics had a better predictive value for both the Nordic countries and those below 50° N latitude. However, temperature variations were unable to explain >1/3 (and usually much less) of the inter-annual variability. The number of statistically

Table 3. Explained variability (adjusted R^2) of the inter-annual differences in wheat and barley yields (first order differences) as explained by individual climatic parameters for April–June. Tmin: mean monthly minimum temperature; Tavg: mean monthly temperature; Tmax: mean monthly maximum temperature; DTR: mean daily temperature range; VAP: water vapor pressure deficit; PREC: precipitation total; WetD: number of precipitation days; PET: potential evapotranspiration; ZIND: Palmer Z-index; PDSI: Palmer Drought Severity Index. Only values of relationships significant at the 0.05 significance level are listed

Wheat

Country/region	Period	Tmin	Tavg	Tmax	DTR	VAP	PREC	WetD	PET	ZIND	PDSI
Finland (FI)	1901–1950			0.10						0.11	0.11
	1951–1990	0.11	0.10	0.08							0.25
	1991–2012										
Sweden (SE)	1901–1950									0.13	
	1951–1990	0.16	0.19	0.15			0.13	0.13	0.18	0.38	0.12
	1991–2012										
Denmark (DK)	1901–1950		0.10				0.18				0.24
	1951–1990			0.11						0.25	
	1991–2012										
Lower Saxony (LS)	1901–1950				0.32		0.45	0.42	0.09	0.36	0.14
	1951–1990						0.64	0.19		0.39	0.08
	1991–2012										
The Netherlands (NL)	1901–1950										0.25
	1951–1990			0.27		0.27	0.42	0.12	0.17	0.34	0.13
	1991–2012						0.20				
Belgium (BE)	1901–1950	0.29	0.19								
	1951–1990			0.17			0.27	0.19	0.19	0.21	0.16
	1991–2012						0.19	0.21			
Czech Republic (CZ)	1901–1950	0.20	0.26	0.29	0.21	0.21			0.30		
	1951–1990	0.10	0.09			0.14					
	1991–2012								0.18		
Austria (AT)	1901–1950	0.14	0.10			0.12					0.14
	1951–1990	0.12	0.09			0.28					
	1991–2012		0.14	0.15	0.14						
Croatia (CR)	1901–1950	0.21	0.27	0.28	0.14				0.19	0.30	
	1951–1990							0.11			
	1991–2012					0.08					
Tuscany (IT)	1901–1950	0.27	0.26						0.35		
	1951–1990										
	1991–2012				0.14						
Bulgaria (BG)	1901–1950	0.11	0.10			0.11	0.20	0.14			
	1951–1990	0.12	0.19			0.18				0.19	
	1991–2012			0.19			0.42	0.02	0.27	0.03	0.13
All countries/regions	1901–1950	0.05	0.03	0.07		0.04	0.02	0.02	0.06		0.07
	1951–1990	0.01				0.04		0.03	0.03		
	1991–2012	0.04	0.03	0.02			0.11		0.03	0.10	0.06

Barley

Country/region	Period	Tmin	Tavg	Tmax	DTR	VAP	PREC	WetD	PET	ZIND	PDSI
Norway (NO)	1901–1950										0.05
	1951–1990	0.30		0.38	0.34		0.12	0.17	0.40		0.29
	1991–2012										
Finland (FI)	1901–1950							0.10			
	1951–1990	0.08		0.10			0.12	0.12	0.18	0.24	0.09
	1991–2012										
Sweden (SE)	1901–1950										
	1951–1990						0.11	0.15		0.23	0.15
	1991–2012										
Lower Saxony (LS)	1901–1950		0.09	0.17					0.21		
	1951–1990				0.17						
	1991–2012	0.27	0.16							0.08	0.12
The Netherlands (NL)	1901–1950										
	1951–1990	0.13		0.12	0.09		0.14	0.12	0.08		
	1991–2012	0.27				0.17					0.22
Belgium (BE)	1901–1950										
	1951–1990										0.10
	1991–2012										
Czech Republic (CZ)	1901–1950	0.31	0.34	0.33	0.13	0.29			0.33	0.33	
	1951–1990	0.09				0.09					
	1991–2012										
Austria (AT)	1901–1950	0.10	0.10	0.10		0.12			0.12	0.17	0.11
	1951–1990										
	1991–2012										
Croatia (CR)	1901–1950	0.30	0.34	0.34	0.16		0.12	0.22	0.38		0.14
	1951–1990										
	1991–2012	0.18	0.19	0.17	0.13				0.17		
Tuscany (IT)	1901–1950	0.30	0.25			0.13		0.15	0.29	0.27	
	1951–1990	0.13									
	1991–2012										0.12
Bulgaria (BG)	1901–1950	0.13	0.16	0.16	0.22	0.16	0.39	0.35	0.17	0.40	
	1951–1990	0.19	0.15		0.12	0.33		0.15			
	1991–2012	0.21				0.22		0.20			
All countries/regions	1901–1950	0.03	0.03	0.04		0.03	0.01	0.04	0.05	0.01	0.06
	1951–1990	0.02	0.03	0.03	0.04	0.05	0.04		0.03	0.04	
	1991–2012	0.06				0.05					0.03

significant relationships between climatic variables and annual yield changed over the individual periods. The number was broadly similar for the first 2 periods, but the ability of inter-annual climatic variations in single parameters to explain yield variability sharply decreased for the 1991–2012 period.

3.3.2. Combined climatic factors

Table 4 indicates that even combining the selected pool of climatic variables for April–June did not explain a large portion of the year-to-year variability in wheat yield between 1901 and 2012, but this also differs strongly by region. Even in the regions where a larger portion of the annual yield variability was explained by climatic factors (e.g. Sweden and Belgium), the mean absolute error (MAE) and root mean square error (RMSE) values indicated that even these

relationships were not useful for yield prediction. However, precipitation, number of frost days and other parameters related to temperature seemed to be essential for explaining yield variability, while this was not the case for drought indicators. In general, precipitation totals played a negative role determining yield variations; i.e. year-to-year increases in precipitation totals suggested a decline in yield, which was also generally the case for Tmax.

For wheat, we recorded only a small number of cases when the relationship with climatic variables changed markedly with the time period (Table 5). It is, however, worth noting that such changes were recorded in Finland and Bulgaria (i.e. in the northern and southeastern end of the area studied). However, climatic variables that were able to explain a reasonable amount of yield variability from 1991–2012 in these 2 countries failed (or showed a much lower capacity) to do so from 1901–1950. This tendency

Table 4. Explained variability (adjusted R^2), relative mean absolute error (MAE) and root mean square error (RMSE) of the inter-annual differences in wheat and barley yield (first order differences) as explained by a combination of climatic parameters for April–June in the period 1901–2012 in the individual European countries/regions. Tavg: mean monthly temperature; Tmin: mean monthly minimum temperature; Tmax: mean monthly maximum temperature; DTR: mean daily temperature range; FRS: number of frost days; PREC: precipitation total; WetD: number of precipitation days; VAP: water vapor pressure deficit; PET: potential evapotranspiration; ZIND: Palmer Z-index; PDSI: Palmer Drought Severity Index. X (Y) identifies significant contributors at the 0.1 significance level, x (y): non-significant contributors. X (x): yield increases with an increasing value of the climatic parameter, Y (y): the opposite relationship. The significance of the single variables should be interpreted with caution as the predictors are mutually correlated, e.g. when Tavg is significant and Tmax is not, the significance of Tmax is probably only 'hidden' by the multicollinearity

	R^2_{adj}	MAE (%)	RMSE (%)	Tavg	Tmin	Tmax	DTR	FRS	PREC	WetD	VAP	PET	ZIND	PDSI
Wheat														
Finland (FI)	0.05	96	134		y	y	y	y			Y	Y		
Sweden (SE)	0.41	77	97	Y					Y				Y	
Denmark (DK)	0.20	86	112			Y	Y	Y		y		y		
Lower Saxony (LS)	0.34	85	105	y				y	Y					
The Netherlands (NL)	0.21	89	111	y	Y		y	y						
Belgium (BE)	0.40	74	93	Y	Y	Y		Y	Y				Y	y
Czech Republic (CZ)	0.20	89	115						Y			Y		
Austria (AT)	0.16	90	127			Y	Y	Y	Y		y			y
Croatia (CR)	0.06	93	122	Y	Y			Y	y		y	y		
Tuscany (IT)	0.25	87	108					Y	Y	Y			Y	Y
Bulgaria (BG)	0.31	90	117					Y	Y	Y	y		Y	y
All countries/regions	0.13	94	125			Y	Y	Y	Y					
Barley														
Finland (FI)														
Norway (NO)	0.05	96	127	y		x	y							
Sweden (SE)	0.28	82	108		y	x	y	Y	X		x		Y	
Lower Saxony (LS)	0.09	94	121	x	y					x		y	y	
The Netherlands (NL)	0.24	83	107	X		Y	X		y				x	Y
Belgium (BE)	0.15	88	121						Y				X	Y
Czech Republic (CZ)	0.20	88	115			Y		Y						
Austria (AT)	0.19	95	126	X		Y	X		y			Y	x	
Croatia (CR)	0.17	91	114					y	Y				X	Y
Tuscany (IT)	0.07	98	139	x	y	x		Y						
Bulgaria (BG)	0.27	89	111	X	Y	X			Y				X	Y
All countries/regions	0.10	95	128			Y	X	Y	Y					

Table 5. As Table 4 for 3 different periods (1901–1950, 1951–1990, 1991–2012). Only those parameters significant at the 0.05 significance level during the 1991–2012 period are listed

Country/region	Period	R^2_{adj}	MAE (%)	RMSE (%)	Tavg	Tmin	Tmax	DTR	FRS	PREC	WetD	VAP	PET	ZIND	PDSI
Wheat															
Finland (FI)	1901–1950	0.01	99	130		y	x	y	y			y	y		
	1951–1990	0.20	88	110		X	Y	X	x			Y	y		
	1991–2012	0.24	81	98		X	Y	X	Y			X	X		
Sweden (SE)	1901–1950	0.51	71	92	Y					X				Y	
	1951–1990	0.51	62	78	y					X				Y	
	1991–2012	0.18	90	101	Y					X				Y	
Denmark (DK)	1901–1950	0.35	82	96			Y	X	Y		x		X		
	1951–1990	0.06	78	108			y	x	y		x		x		
	1991–2012	0.25	71	99			Y	X	Y		X		X		
Lower Saxony (LS)	1901–1950	0.13	91	109	Y				y	Y					
	1951–1990	0.50	64	81	x				X	Y					
	1991–2012	0.71	51	65	Y				Y	Y					
The Netherlands (NL)	1901–1950	0.32	80	101	y	x			x	y					
	1951–1990	0.24	81	104	x	y			y	x					
	1991–2012	0.29	75	94	X	Y			Y	Y					
Belgium (BE)	1901–1950	0.43	66	85	X	Y	Y		Y	x				y	Y
	1951–1990	0.52	58	76	x	y	y		y	Y				X	Y
	1991–2012	0.59	57	66	X	Y	Y		Y	Y				X	Y
Czech Republic (CZ)	1901–1950	0.33	80	96					y				Y		
	1951–1990	0.04	98	118					y				Y		
	1991–2012	0.34	70	95					Y				Y		
Austria (AT)	1901–1950	0.27	72	92		y	X	y	y			x			Y
	1951–1990	0.40	73	89		y	x	y	y			Y			Y
	1991–2012	0.49	69	79		Y	X	Y	Y			X			X
Croatia (CR)	1901–1950	0.32	55	70	y	x		x	x			y	y		
	1951–1990	0.01	86	109	x	y		y	y			y	y		
	1991–2012	0.62	61	74	Y	X		X	Y			Y	Y		
Tuscany (IT)	1901–1950	0.36	65	87					x	y	y			X	Y
	1951–1990	0.31	75	94					Y	Y	Y			X	Y
	1991–2012	0.47	69	79					Y	Y	Y			X	Y
Bulgaria (BG)	1901–1950	0.15	75	101						x	x	y		y	X
	1951–1990	0.44	72	92						Y	X	y		x	X
	1991–2012	0.61	58	75						Y	X	X		X	Y
All countries/ regions	1901–1950	0.16	91	120			Y	X	Y	Y					
	1951–1990	0.16	90	117			Y	X	Y	Y					
	1991–2012	0.17	95	118			Y	X	Y	Y		(Table continued on next page)			

was also found for Lower Saxony. However, in the rest of the countries, the explained variability did not change to any great extent. While one would expect the most variability to be explained by the regression analysis of the data from 1991–2012 (as climatic variables were selected using these data), this was not the case, and 4 of the 11 regions showed that a higher or much higher proportion of the variability was explained in the earlier periods. Fig. 4a shows that the adjusted R^2 (i.e. the explained variability) was higher and the relative RMSE was lower for the period from 1991–2012 than for 1901–1950 and 1951–1990. This indicates that factors affecting yield variability indeed changed over time, although this change must have been relatively subtle.

3.4. Climatic effects on barley yields

3.4.1. Individual climatic parameters

The first order differences of the selected climatic parameters for barley (Table 3) were, in general, poor predictors of yield change. Only minimum temperatures and water vapor pressure deficits showed significant (yet weak) relationships across all 3 periods. Yields across all regions and the whole period studied responded significantly to all parameters, with the exception of potential evapotranspiration — but as observed for wheat, only an insignificant fraction of yield variation was explained by the variation of individual climatic indicators. While a larger portion of yield variation was explained for individual re-

Table 5 (continued)

| Country/region	Period	R^2_{adj}	MAE (%)	RMSE (%)	Tavg	Tmin	Tmax	DTR	FRS	PREC	WetD	VAP	PET	ZIND	PDSI
Barley															
Finland (FI)	1901–1950														
	1951–1990														
	1991–2012														
Norway (NO)	1901–1950	0.00	94	113	x		y	x							
	1951–1990	0.48	64	80	X		Y	X							
	1991–2012	0.05	88	123	Y		X	Y							
Sweden (SE)	1901–1950	0.09	79	101		y	x	x	y	x		y		y	
	1951–1990	0.40	69	83		x	y	x	y	X		y		Y	
	1991–2012	0.58	51	69		Y	X	Y	Y	X		X		Y	
Lower Saxony (LS)	1901–1950	0.24	77	96	y	x					x		Y	y	
	1951–1990	0.00	94	120	y	y					x		x	y	
	1991–2012	0.60	52	63	X	Y					X		Y	Y	
The Nether-lands (NL)	1901–1950	0.13	95	124	x		y	x		x				y	X
	1951–1990	0.39	71	84	x		y	x		Y				X	Y
	1991–2012	0.60	54	63	X		Y	X		Y				X	Y
Belgium (BE)	1901–1950	0.00	93	147						y				x	Y
	1951–1990	0.17	83	111						Y				X	Y
	1991–2012	0.32	79	94						Y				X	Y
Czech Republic (CZ)	1901–1950	0.28	85	101		Y			y						
	1951–1990	0.11	88	110		Y			y						
	1991–2012	0.24	84	103		Y			Y						
Austria (AT)	1901–1950	0.13	91	132	x		y	x		x			y	y	
	1951–1990	0.00	85	105	x		y	x		x			y	y	
	1991–2012	0.67	49	64	X		Y	X		Y			Y	X	
Croatia (CR)	1901–1950	0.36	76	96					y	y				X	Y
	1951–1990	0.09	93	108					y	Y				X	Y
	1991–2012	0.32	72	88					Y	Y				X	Y
Tuscany (IT)	1901–1950	0.09	71	91		x	y	x	x						
	1951–1990	0.36	81	103		Y	X	Y	Y						
	1991–2012	0.40	74	95		X	Y	X	Y						
Bulgaria (BG)	1901–1950	0.42	69	88		X	Y	X		y				x	y
	1951–1990	0.22	81	100		y	x	Y		y				x	Y
	1991–2012	0.57	57	71		X	Y	X		Y				X	Y
All regions	1901–1950	0.07	94	131	y	x	x	Y					Y		Y
	1951–1990	0.12	91	119	y	x	x	X					x		Y
	1991–2012	0.15	92	117	X	X	Y	X					Y		Y
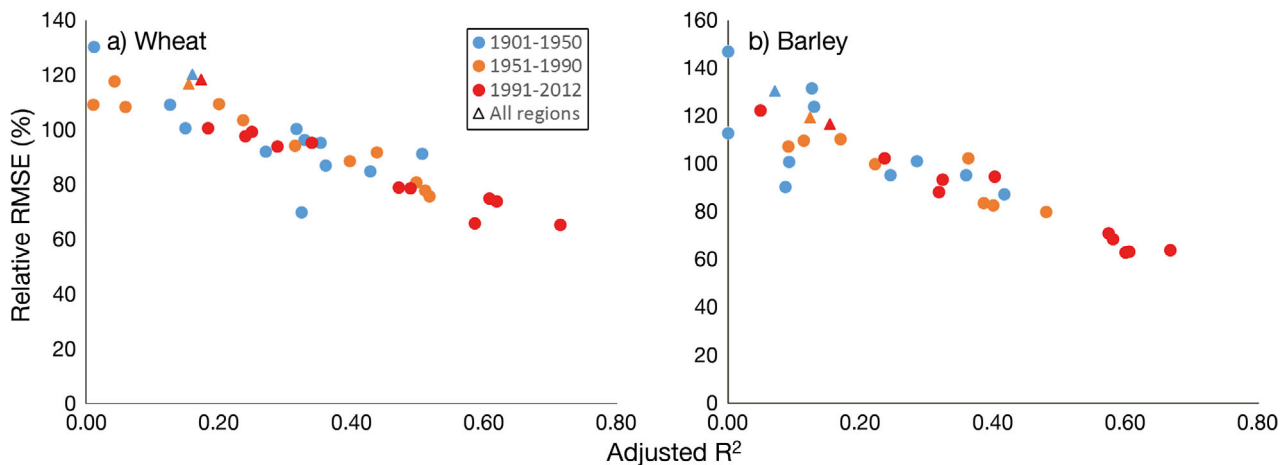
Fig. 4. Relationship between adjusted R^2 and mean absolute error of the best-fit stepwise regression function between first order differences of climatic variables (see Table 4) and inter-annual yield variations for (a) wheat and (b) barley. Individual dots represent regions listed in Table 4, with triangles showing the results for all regions

gions, it was not consistent across the periods. Compared to those for wheat, the adjusted R^2 values were generally smaller. The sharp decline in the ability of single factors to explain yield variations in the period from 1991–2012 was even stronger for barley than it was for wheat.

3.4.2. Combined climatic factors

Combined climatic factors from April–June using the data from 1901–2012 explained a relatively small share of the year-to-year variability in barley yield when all regions were pooled, and their predictive ability was lower than they were for wheat yield (Table 4). Interestingly, no significant relationship was found for Finland, which is likely due to a later harvest occurring in this country (mid- to late August) compared to other regions. For Norway, Lower Saxony and Tuscany, the explained variability in yield was <10%. Only in the case of Sweden (southern Sweden, where most agriculture is concentrated), the Czech Republic and The Netherlands could >1/5 of the year-to-year variability be explained by the suite of selected climatic factors over the entire 1901–2012 period. The MAE and RMSE values were similar to those observed for wheat, while the overall influence of climatic patterns appeared to be smaller. For barley, year-to-year yield variations, precipitation totals, number of frost days, daily temperature range and maximum temperatures (all for April–June) seemed to be the most influential of the climatic drivers tested. Similar to the results for wheat, year-to-year increases in precipitation, frost occurrence and maximum temperature from April–June were associated with a decline in barley yield. Short-term droughts seemed to lead to lower yields in Belgium, Croatia and Bulgaria, while long-term droughts in general lowered the overall production level.

Clear evidence of a changing relationship between climatic factors and changes in the yield of barley exist (Table 5). Similar to the observations for wheat, these changes were recorded in northern and southeastern Europe (Norway, Sweden and Lower Saxony compared to Tuscany and Bulgaria). In addition, climatic variables that were able to explain a fairly large portion of the inter-annual yield variability from 1991–2012 showed a much lower predictive ability for the 1901–1950 and 1951–1990 periods. Fig. 4b shows a visible difference in the adjusted R^2 and RMSE values between the results of the 1991–2012 period and those of the 1901–1950 and 1951–1990 periods, suggesting that the influences of climate on annual crop yields have been changing over the periods considered. It seems that the influence of climatic variables on crop yields has increased in the period from 1991–2012.

4. DISCUSSION

While climate plays an important role in limiting the geographical distribution of particular crops (Elsgaard et al. 2012), it also influences overall production levels (see Fig. 3). The low yields generally reported for the 3 most southern regions are from areas where cereal yields are considered to be limited by water availability, heat stress and the short duration of the grain filling period (Ewert et al. 2005). Cereals in these regions are complemented by perennial crops, such as olive, grapes and fruit trees, as they have deeper root systems and can therefore better withstand long dry periods. Crops in this area also tend to be affected by extreme weather events (such as hail and storms) more often, which can reduce or completely destroy the crop in a given year (Olesen et al. 2011). Irrigation is important for crop production in many Mediterranean countries due to high levels of evapotranspiration and limited rainfall. On the other hand, the most productive regions in Europe in terms of climate and soils are located in the Great European Plain, stretching from southeast England through France and Benelux to Germany. In addition to a milder and more favorable Atlantic climate in these regions (see Fig. 1), the more favorable topography should also be considered, which makes the use of highly mechanized agricultural techniques more efficient. These regions also have better supported rural areas, where rural sectors have a history of receiving comparatively higher levels — and/or perhaps better-managed — research and infrastructure investments. Central Europe (represented by the Czech Republic and Austria) has comparatively drier conditions and a greater range of variation in annual temperatures, limiting the range of crops that can be grown and the yields of those that are grown.

Our analyses showed that overall crop production levels can be at least partly attributed to the prevailing climatic conditions (see Fig. 3). This means that the extent of the progress made in increasing yield in the 20th century has been shaped both by the climatic patterns (determining suitability) and by technological and socio-economic changes. For example, wheat and barley yield levels, as well as the rates of their increase, in the Czech Republic and Austria (or Croatia and Italy) were found to be approximately equal

(comparing results in Fig. 3) despite the fact that these countries, which are similar climatically (as shown in Fig. 1), followed very different paths in their development (see Table 1). In contrast, yield levels in Denmark, Belgium, The Netherlands and Lower Saxony were markedly higher across all time periods analyzed than those of the rest of the group. This is to a great extent attributable to more favorable climatic conditions, because all 4 countries are in the same environmental zone (Atlantic North; Fig. 1a), characterized by mild winters, sufficient and well distributed precipitation and cool summers, among other factors (Metzger et al. 2005). In addition, the overall structure of the farming sector, a relatively fast adoption of modern technologies driven by advanced agricultural research, and past and present investment levels have also supported the attainment of higher yields in these countries than in other countries.

As wheat and barley yields are limited in northern Europe by cool temperatures (Holmer 2008) and in southern Europe by high temperatures and low rainfall (Reidsma & Ewert 2008) it was hypothesized that the response to warming within these regions is likely to differ. Indeed, in Finland and Norway we found an increasing influence of temperature, and in Bulgaria and Tuscany of drought, after 1951 (Table 5). Somewhat surprisingly, variations in maximum temperature were shown to explain a portion of yield variability only in some northern and northwestern regions (Table 5), which might be explained by the use of cultivars adapted to the high temperatures of the southern regions. However, this adaptation in the choice of varieties planted and in management is likely also to contribute to generally lower yields. A study by Olesen et al. (2011) seems to support this argument, showing that in Finland, a small yield increase has occurred during the last 10–20 yr that is partly linked to increasing temperatures, which has allowed earlier sowing and a prolonged growing season (Rötter et al. 2013, Peltonen-Sainio & Jauhiainen 2014, Palosuo et al. 2015). On the other hand, the wheat yields in Greece have been declining, which is likely also linked to the increase in temperatures.

The significance of the single variables as presented in Table 4 is likely influenced by the multicollinearity of the individual predictors, and must be interpreted carefully (Farrar & Glauber 1967). For example, when Tavg is significant and Tmax is not, the significance of Tmax is probably only 'hidden' by the multicollinearity. However, the adjusted R^2 values are presented for the whole model and thus the predictability skill of the model is not overestimated. On the other hand, adjusted R^2 might even underestimate predictability, as R^2 is 'adjusted' by the number of variables, but some variables bring only little new predictive power (because of the multicollinearity). Nevertheless, because of the relatively large number of variables used, the 'adjusted' version of R^2 is more realistic that the non-adjusted R^2.

Overall, wheat yields in several European countries have been shown to increase in variability, which can be linked to climatic variability (Olesen et al. 2011). The stagnating wheat (and barley) yields across European regions (as depicted in Fig. 3) have been found to be co-determined by the warming climate (Brisson et al. 2010) and/or by changes in management, especially in the changes to fertilization application due to environmental regulations (Finger 2010, Palosuo et al. 2015, Peltonen-Sainio et al. 2015). Gömann et al. (2015) reported that wheat crops have been extended to less favorable sites during the last decades in Germany. Regardless of the cause, post-1990 yield variability is, in absolute terms, significantly higher in most of the evaluated regions, while in terms of relative variability (accounting for the increase in mean yield), it remains approximately stable. The higher variability in yields with higher yield levels is coupled to the greater impact of yield-reducing factors, such as elevated temperatures that shorten crop growth durations, or greater water consumption by high-yielding crops that enhance the yield reductions caused by drought (Liu et al. 2013).

In the period from 1991–2012, only the combination of climatic factors, and not any single factor, could explain yield variability to some extent (compare results in Tables 3 & 5). This indicates that with the changes brought by technological progress, the influence of climate on yields may have become more complex than in the past. This might also signal that the climatic trends are becoming at least as important as the technological trends (e.g. new machinery, better seeds, new cultivars, fertilizers and pesticides) that have dominated European agriculture, especially in the 1951–1990 period (Fig. 3c,d). In addition, other factors, such as soil compaction and reduced soil organic matter content and fertility are important, and may increase the vulnerability of crops to climatic constraints, at least locally (e.g. Peltonen-Sainio et al. 2015). The increasing availability of fertilizers fostered a shift to growing crops in formerly less productive sites (e.g. those with sandy soils), which might have increased the harmful impact of climatic factors. On the other hand, pests and nutrient deficiencies limited crop growth in the earlier periods analyzed here, but have become less important in many regions in recent decades. There

is at least local evidence that in some regions, agri-environmental policies and economic challenges faced by farms (e.g. uncertainty over rented lands) have encouraged reduced use of pesticides and nutrients and less balanced crop rotations in recent years, possibly impacting yields and yield variation (Peltonen-Sainio et al. 2015). Overall yield growth rates across the regions in 1991–2012 were similar to those based on the data from 1901–1950. From a long-term perspective, this constitutes a question of a major importance that should be addressed across Europe.

Although food security in Europe is thought to be less dependent on the climate due to technologically sophisticated agricultural practices (Brown & Funk 2008), our results indicate that climatic variability still has a significant influence on European wheat and barley productivity. However, the key drivers for changes in productivity differ even within similar environmental regions, and they seem to change with time. Efforts to increase the preparedness of the farmers to adapt to climatic variations are needed, and should result in concrete measures enabling sustainable and more stable food production. This is even more urgent when considering the fact that the present study did not account (due to data constraints) for many types of adverse events that can negatively influence yields. This has been reported for several types of extreme events over recent decades in Germany (Gömann et al. 2015), and a potential increase in the frequency of adverse events was noted by Trnka et al. (2011, 2014, 2015), showing the risk of a several-fold increase in the frequency of events known to lead to decreases in crop yield.

5. CONCLUSIONS

This study shows that there is strong (and sometimes counterintuitive) geographical specificity by which factors determine yield variations. For example, while precipitation is amongst the most important factors explaining year-to-year yield changes in Belgium, The Netherlands and Lower Saxony, the indicators of drought variations were found to have only limited explanatory power, even in countries where wheat and barley production is known to be limited by water availability.

It is clear that the influence of climatic variables on yields of wheat and barley has increased in the period from 1991–2012 in most countries. It is important to note that the different set of predictors explained yield variability in this period better than in the periods 1901–1950 and 1951–1990. This leads us to conclude that climate change is altering the sensitivity to particular climatic factors.

Variations in climatic factors (combined together) explained between 18 and 71% of wheat yield variability and between 5 and 60% of barley yield variability in the 1991–2012 period. The ability to explain yields based on climatic factors increases (albeit not markedly) when we take into account country-specific time windows, and shows that the April–June period is critical for yield formation of barley and wheat in most of the studied region.

We also conclude that changes in the climate–yield relationships would likely be more easily established over smaller and more homogenous regions than over those for which we were able to collect corresponding data. However, such data are not available — at least not for the countries we analyzed — and thus we conclude that the study of climate–yield relationships in Europe is significantly hampered by limited accessibility of agricultural statistics, especially prior to 1961. Despite great effort in collecting data on the 12 European regions studied here, it was difficult to produce a sufficiently complete database on crop yields that covered the period between 1901–2012, even for the 2 most widely grown crops. As we primarily selected regions that were not significantly affected by changes in borders, the situation in other regions of Europe is likely to be even worse. The lack of an accessible and reliable NUTS4-level yield database for European Union or Europe in general (similar e.g. to the county yield statistics in the USA) hampers not only this type of research activity in Europe, but limits any studies linking the yield of key agricultural products to environmental factors.

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