Received: 9 March 2021 | Revised: 15 September 2021 | Accepted: 23 December 2021

DOI: 10.1002/fes3.372

Food and Energy Security Open Access WILEY

ORIGINAL ARTICLE

Will temperature and rainfall changes prevent yield progress in Europe?

Marta S. Lopes

Sustainable Field Crops Programme, IRTA (Institute for Food and Agricultural Research and Technology), Lleida, Spain

Correspondence
Marta S. Lopes, Sustainable Field Crops Programme, IRTA (Institute for Food and Agricultural Research and Technology), Lleida 25198, Spain.
Email: marta.dasilva@irta.cat

Funding information
Spanish Ministry of Economy and Competitiveness, Grant/Award Number: RTA2015, -00072-, C03 and -01

Abstract

Concerns about the effects of global warming on crop yields have been raised due to stagnating yield progress in recent years. However, an understanding of the effects of changes in temperature and rainfall throughout the crop cycle on historical yield progress is lacking in Europe (EU). In this study, positive wheat, barley, rice, and maize yield progress in the EU (1961–2019) was significant, with rates of 0.05, 0.04, 0.05, and 0.07 $Tha^{-1}year^{-1}$, for the four crops respectively. Much of this progress has been sustained by Eastern European countries (EE), which had the highest yield progress rates. On average, in the case of wheat and barley, a temperature increase of 1°C in the winter resulted in yields increasing by +0.33 Tha^{-1} in EE. This was potentially due to decreasing cold damage and improved photosynthesis and vegetative growth, supporting positive yield progress. Recent historical (2001–2019) rates of wheat, barley, rice, and maize yield progress were positive in all EU regions except Western Europe (WE), barley in Southern Europe (SE) and wheat in Northern Europe (NE). Stagnated wheat, barley and rice yields in WE were not explained by temperature or rainfall using direct correlations of observed data. However, May and July temperatures were associated with wheat yields in NE (−0.30 $Tha^{-1}°C^{-1}$), barley in SE (−0.14 $Tha^{-1}°C^{-1}$) and maize in WE and SE (−0.42 and −0.39 $Tha^{-1}°C^{-1}$). With increasing temperatures becoming less than optimal for photosynthesis, reducing grain filling duration and increasing drought episodes, crop yields have stagnated for wheat in NE and barley in SE. With consistent increases in temperature and water evaporative demand expected in the future, the interplay among genetic adaptation, increased crop cycle duration, drought tolerance, sowing dates, smart irrigation and sustainable practices may require thorough regional testing to maximise the yields of wheat, barley and maize in Europe.

KEYWORDS

barley, global warming, heat adaptation, maize, rice, wheat

1 | INTRODUCTION

Crop yield progress defined here as the slope of the linear regression function between average yield changes and time provides information about how well crop productivity can meet global demands without additional land. However, yield progress stagnation has been reported in Europe (Brisson et al., 2010; Ray et al., 2012). Moreover, Asseng et al. (2015) using 30 different wheat crop models indicated that warming is already slowing yield gains at most wheat-growing locations (6% decreases were projected for each °C). Similarly, Lobell et al. (2011) indicated 3.8% and 5.5% decrease in wheat and maize yields, respectively, linked to weather. Evaluation of yield progress is crucial and needs reassessment every 10–20 years to identify new strategies and policies before yields start to collapse. A potential cause for stagnant crop yields is genetics, where varieties attain their full potential in terms of grain production; however, yield progress associated with crop improvement in various international breeding programmes has been largely demonstrated to be positive and significant with no signs of slowing down (Aisawi et al., 2015; Crespo-Herrera et al., 2018; Lopes et al., 2012) putting other farming-related strategies and climate in the spotlight to justify stagnation.

Rising temperatures have been identified as an important yield-reducing agent. Using sophisticated modelling, Semenov and Shewry (2011) concluded that the frequency of heat stress around flowering will increase in the future and affect yield negatively. More recently, Zhao et al. (2017) also predicted yield reductions with rising temperatures. Moore and Lobell (2015) showed that climate trends can explain 10% of the slowdown in wheat and barley European yields, with changes in agriculture and environmental policies possibly responsible for the reminder. While causes for slow or stagnated yield progress have been associated with rising temperatures, correlative analysis with past and current yield and weather data are scarce (e.g. Moore & Lobell, 2015). The struggle to identify correlations between temperature and crop yield probably relates to its erratic nature and the comparatively (to average weather) low frequency of extraordinary hot weather and other confounding effects including nutrient, water availability, pest and disease control resulting from changes in regulatory policies. Despite the difficulties to separate on a global scale the effects of nutrients, water availability, pest and disease control from temperature effects on grain yields, this study attempted to determine associations between monthly temperature and grain yield. These considerations originated from the observation that the wheat crop is more sensitive to heat at the reproductive stages than at any other stage (Hatfield & Prueger, 2015; Saini & Westgate, 1999). If meiosis and grain formation occur around May to July, it is sensible to consider that temperatures during those months will demonstrate a clear negative effect on historical grain yield data and this was one of the objectives of this study. For that purpose, historical yield (for wheat, barley, rice and maize) and temperature data from FAOSTAT were used to determine the nature and magnitude of temperature and rainfall effects on grain yields across Europe. Firstly, historical (1961–2019 and recent between 2001 and 2019) yield progress rates were analysed in all EU countries and sub-regions. Secondly, associations between historical monthly temperatures and grain yield were analysed, key months identified (when temperatures effects are significant) and the magnitude and nature of those effects defined. Finally, strategies were suggested to support future yield progress.

2 | MATERIALS AND METHODS

2.1 | Crop yield, temperature and rainfall data

The crop yields and temperature changes used in this study were downloaded from the FAOSTAT webpage (http://www.fao.org/faostat/en/#data/QC). The FAOSTAT temperature change domain disseminates statistics of mean surface temperature change by country, with annual updates. The current dissemination covers 1961–2019. Statistics are available for monthly, seasonal and annual mean temperature anomalies, that is, temperature changes with respect to baseline climatology, corresponding to the period 1951–1980. The average monthly temperature and precipitation for the same set of countries and years were obtained from the Climate Change Knowledge Portal (https://climateknowledgeportal.worldbank.org/download-data). All data are based on publicly available GISTEMP data and the global surface temperature change data distributed by the National Aeronautics and Space Administration Goddard Institute for Space Studies (NASA-GISS).

2.2 | Statistical analysis

Regression analysis was performed with SAS (version 9.4) using Proc REG, and both linear and quadratic functions were tested in all sets of comparisons. Graphs with correlations and regression equations were designed using Microsoft Office Excel. Two-way hierarchical cluster of average monthly temperatures and rainfall between 2001 and 2019 in the various EU sub-regions was performed using JMP14.

2.3 | Literature analysis

Network analysis of available literature (1990–2021) was obtained from Web of Science database (sum of all results from the following search keywords: wheat and yield and "climate change"; barley and yield and "climate change"; maize and yield and "climate change"; rice and yield and "climate change"). The search results (around 8000 papers) were used in VOSviewer to calculate clusters of the highest-ranking number of co-occurrences with the searched keywords available in the literature. Only the first 150 items with the highest-ranking co-occurrences were selected for network analysis.

3 | RESULTS

3.1 | Wheat, barley, rice and maize yield progress in Europe

Europe delivered positive crop yields from 1961 to 2019 at rates of 0.05 $Tha^{-1}year^{-1}$ for wheat and rice, respectively, 0.04 $Tha^{-1}year^{-1}$ for barley, and 0.07 $Tha^{-1}year^{-1}$ for maize (Figure 1). The highest yields were observed in western and northern Europe (WE and NE) for wheat and barley, whereas rice and maize yields were highest in western (WE) and southern Europe (SE) (Figure 1). The most notorious wheat yield stagnation was observed in WE and NE, and barley yield has been stagnant in WE and SE, as explained by non-significant linear regressions over the past 19 years (Table 1 and Figure 1). In Eastern Europe (EE), where yields were the lowest, on average, positive significant yield progress was reported over the past 19 years for all crops (Table 1 and Figure 1). Maize and rice yields have been stagnant for the past 19 years in WE; however, rates of yield progress continue to be positive in all other EU regions (Table 1).

On a country-by-country basis, yield progress was calculated as the slopes of the regression between grain yield and year (2001–2019), as shown in Table S1 for wheat, barley, rice and maize. All countries in WE had non-significant yield progress, except barley in Austria, Germany and the Netherlands and maize in Belgium and Switzerland all with positive yield progress (Table S1). All EE countries, however, reported a significant linear yield progress for wheat, barley, rice and maize (except

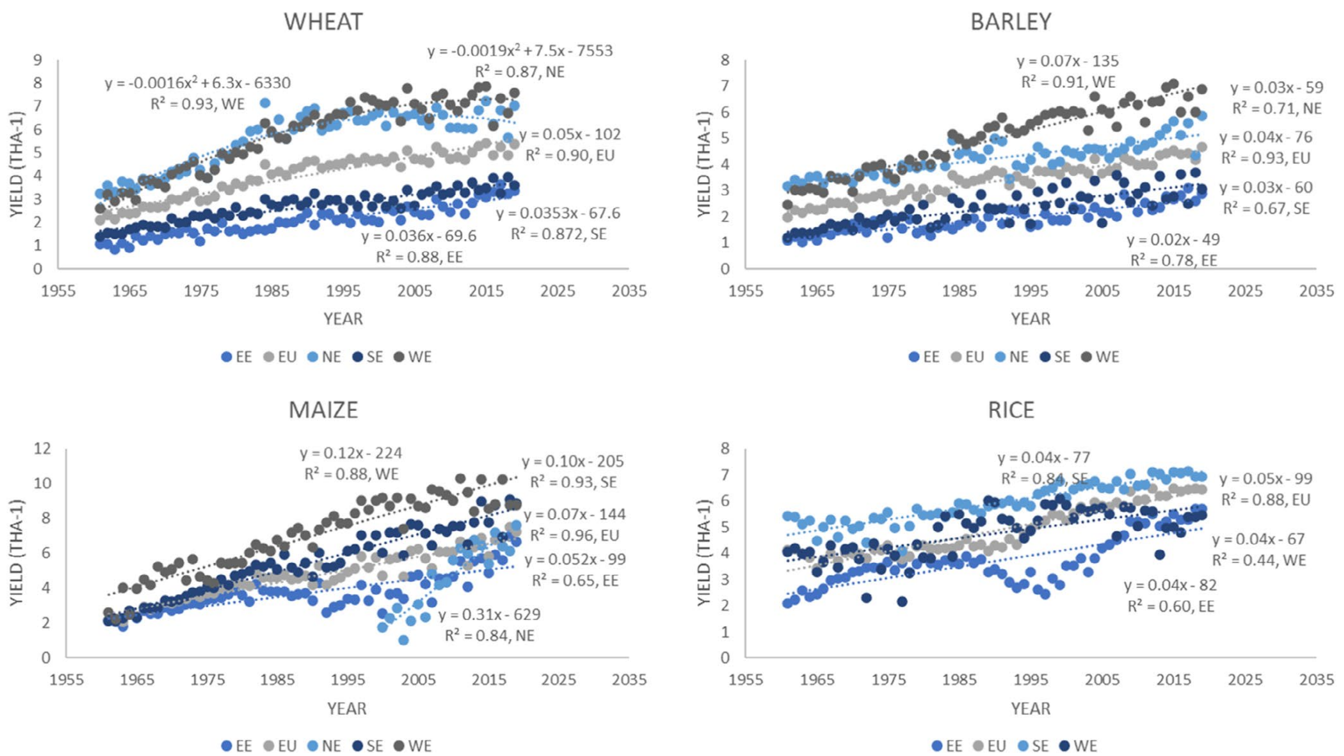

FIGURE 1 Yield progress in Europe from 1961 to 2018 in wheat, barley, maize and rice. All regression equations are significant at $p < 0.05$: EE, Eastern Europe; NE, Northern Europe; SE, Southern Europe; WE, Western Europe. Eastern Europe: Belarus, Bulgaria, Czechia, Hungary, Poland, Romania, Russian Federation, Slovakia and Ukraine; Northern Europe: Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, Norway, Sweden and United Kingdom; Southern Europe: Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Malta, Montenegro, Portugal, Serbia, Slovenia and Spain; Western Europe: Austria, Belgium, France, Germany, Luxemburg, Netherlands and Switzerland

	1961–1980		1981–2000		2001–2019		GY		
	S	R^2	S	R^2	S	R^2	AVG	MAX	MIN
Wheat									
WE	**0.11**	**0.83**	**0.11**	**0.87**	0.01	0.01	5.7	7.9	2.6
EE	**0.04**	**0.68**	**0.03**	**0.44**	**0.06**	**0.6**	2	3.6	0.8
SE	**0.06**	**0.91**	0.02	0.25	**0.05**	**0.57**	2.7	3.9	1.4
NE	**0.09**	**0.81**	0.04	0.21	−0.01	0.01	5.6	7.2	3.3
EU	**0.05**	**0.82**	**0.07**	**0.91**	**0.05**	**0.6**	**2.8**	**4.4**	**1.1**
Barley									
WE	**0.07**	**0.75**	**0.09**	**0.82**	0.04	0.2	6.2	7.1	5.3
EE	**0.03**	**0.38**	**0.02**	**0.25**	**0.04**	**0.43**	2.4	3.1	1.9
SE	**0.05**	**0.81**	**0.05**	**0.3**	0.03	0.11	2.9	3.6	1.8
NE	**0.03**	**0.56**	0	0	**0.05**	**0.45**	4.8	5.7	4.3
EU	**0.03**	**0.52**	**0.04**	**0.74**	**0.05**	**0.63**	**3.3**	**3.9**	**2.9**
Rice									
WE	−0.03	0.06	**0.06**	**0.28**	−0.04	0.15	4.7	6.1	2.2
EE	**0.08**	**0.86**	**−0.05**	**0.51**	**0.13**	**0.84**	3.7	5.7	2.1
SE	0	0	**0.05**	**0.72**	**0.03**	**0.52**	5.9	7.1	4.1
EU	0.01	0.09	**0.07**	**0.75**	**0.05**	**0.8**	**4.8**	**6.5**	**3.4**
Maize									
WE	**0.13**	**0.57**	**0.16**	**0.87**	0.03	0.06	7	10.3	2.2
EE	**0.09**	**0.93**	−0.03	0.14	**0.16**	**0.7**	3.7	7	1.8
SE	**0.14**	**0.97**	**0.08**	**0.49**	**0.10**	**0.38**	5.6	9.1	2.1
NE	**NA**	**NA**	**NA**	**NA**	**0.32**	**0.82**	4.8	7.6	1
EU	**0.12**	**0.97**	**0.04**	**0.31**	**0.09**	**0.48**	**4.7**	**7.5**	**2.1**

TABLE 1 Yield progress over time in groups of EU countries (Western Europe, Northern Europe, Southern Europe and Europe all) as indicated in slope (S in Tha^{-1} $Year^{-1}$) and R^2 of regression equations of year and grain yield for wheat, barley and rice. Eastern Europe: Belarus, Bulgaria, Czechia, Hungary, Poland, Romania, Russian Federation, Slovakia and Ukraine; Northern Europe: Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, Norway, Sweden and United Kingdom; Southern Europe: Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Malta, Montenegro, Portugal, Serbia, Slovenia and Spain; Western Europe: Austria, Belgium, France, Germany, Luxemburg, Netherlands and Switzerland; Average, maximum and minimum grain yields (GY) between 1961 and 2019 are shown. Bold values denote statistical significance at the $p < 0.05$ level

barley in Belarus, rice in Hungary and maize in Czechia and Hungary, where regressions were non-significant). Few NE countries reported significant wheat yield progress, including Estonia, Latvia and Lithuania (Table S1). However, for barley, significant yield progress was reported in NE, except in Denmark, Norway and Sweden, where barley yields were stagnant. Most countries in SE showed significant wheat yield progress, except in Spain, which showed stagnant wheat yields. Despite stagnant barley yields in SE (average of all countries), only Albania and Spain reported stagnant grain yields, while barley yield progress in Bosnia, Croatia, Greece, Italy, Malta, Portugal and Slovenia was significant (Figure 1 and Table S1).

Rice yield progress was significant in the EE and SE countries; however, for wheat and barley, the WE yields were stagnant (Table S1).

Maize yield progress was significant in most EE and SE countries, while in NE and WE, yield progress was only significant in Denmark and Lithuania (NE) and Belgium and Switzerland (WE) (Table S1).

3.2 | Average temperature and rainfall trends in Europe between 1961 and 2019

The average annual temperatures showed a significantly increasing trend in all EU sub-regions (Figure 2). The rates of temperature increase were similar in all four sub-regions, at 0.03°$Year^{-1}$. Winter rainfall was found to decrease significantly at a rate of −1.3 mm a year in EE, whereas in NE, this rate was found to increase significantly at 1.5 mm a year in the winter and at a 1.3 mm a year increase in the summer. Western and southern countries showed no significant changes in rainfall (Figure 2).

3.3 | Monthly temperature and rainfall change effects on wheat, barley, rice and maize yields in Europe between 2001 and 2019

The analysis of the effects of temperature on wheat, barley, rice and maize grain yields over the past 19 years

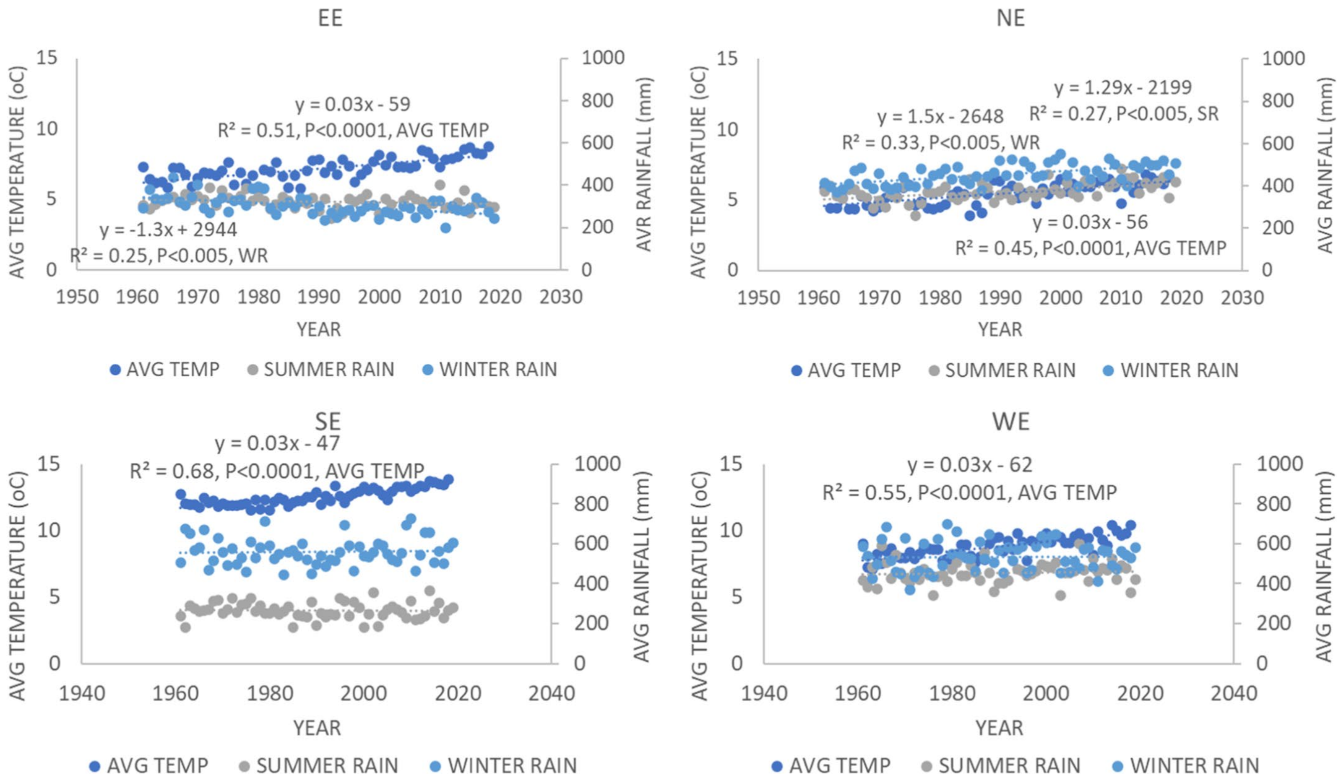

FIGURE 2 Historical average temperature, summer and winter rainfall (SR and WR for summer and winter, respectively, from 1961 to 2019) in European sub-regions: EE, Eastern Europe; NE, Northern Europe; SE, Southern Europe; WE, Western Europe. Eastern Europe: Belarus, Bulgaria, Czechia, Hungary, Poland, Romania, Russian Federation, Slovakia and Ukraine; Northern Europe: Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, Norway, Sweden and United Kingdom; Southern Europe: Albania, Bosnia and Herzegovina, Croatia, Greece, Italy, Malta, Montenegro, Portugal, Serbia, Slovenia and Spain; Western Europe: Austria, Belgium, France, Germany, Luxemburg, Netherlands and Switzerland. Regression equations are shown if statistically significant. Slopes of the regression lines indicate the rate of temperature or rainfall changes

(from 2001 to 2019) in EU countries was conducted by linking monthly temperature and rainfall in each EU region with the correlation among temperature, rainfall and yields (Figure 3).

With the coolest winters in Europe, increasing winter temperatures (December, February and average winter temperatures) in EE countries were found to positively affect wheat and barley grain yields (2001–2019). Similarly, increasing temperatures in the spring and summer (April–September) were positively associated with maize and rice grain yields (Figure 3). On average, temperature increases (annual average) of 1°C in the EE region increased yields of wheat, barley, rice and maize by 660, 590, 670 and 940 kg ha^{-1} respectively (Table S2). The temperature effects in rice yields were significant in the EE countries (Figure 3 and Table S2), particularly in the summer months of April, June, August and September. On average, with an increase of 1°C in the previous months, rice yields increased by 375 kg ha^{-1} (calculated as the average slopes across April, June, August and September) (Table S2). Similarly, in the second coolest and wettest EU region, NE, the winter temperatures were found to be positively correlated with wheat and barley yields (increases of 1°C in the winter months increased the yields of wheat and barley by 210 and 180 kg ha^{-1}) (Table S2). However, a negative correlation was observed between the temperatures in May and July with the wheat and barley yields (when temperature increased by 1°C in July, wheat and barley yields decreased by −330 and −250 kg ha^{-1}). The total and winter rainfall were positively correlated with wheat and barley yield in NE. On average, an increase of 1 mm of rainfall in NE countries resulted in an increase of 6, 5 and 11 kg ha^{-1} in the wheat, barley and maize yields respectively (Table S2). Western countries with temperate climates did not show temperature effects in the wheat, barley and rice yields; however, in maize, summer rainfall was found to have a positive correlation with yield, whereas July and the average summer temperature were negatively correlated with maize yield. In WE countries, an increase of 1°C in the summer resulted in a decrease in maize yields by 850 kg ha^{-1}. Moreover, an increase of 1 mm in rainfall in the summer resulted in an increase in maize yields by 10 kg ha^{-1} (Figure 3 and Table S2). The

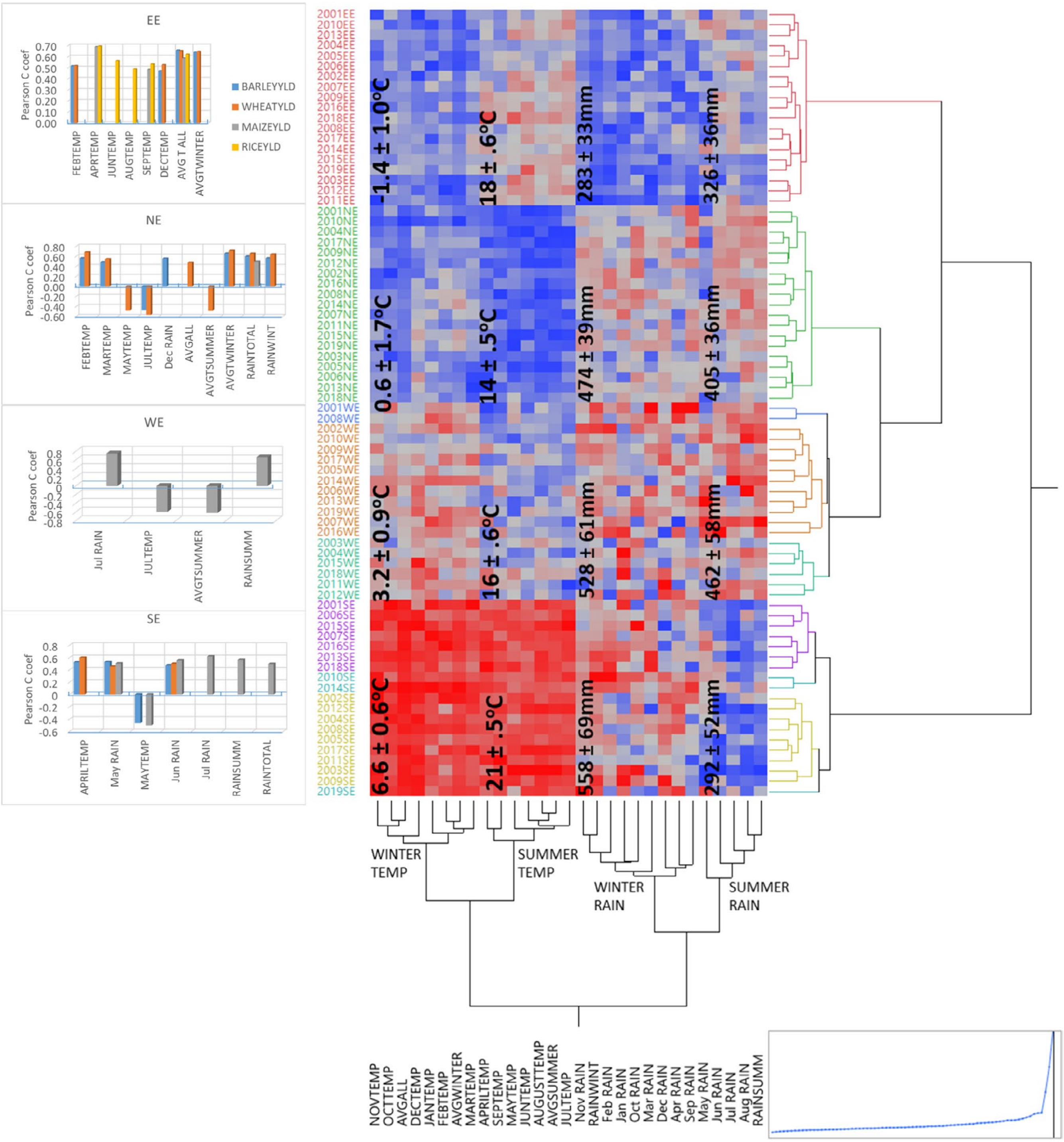

FIGURE 3 Hierarchical two-way clustering of temperature and rainfall in EU sub-regions throughout 2001–2019: EE, Eastern Europe; NE, Northern Europe; WE, Western Europe; SE, Southern Europe. Significant correlations between monthly temperature and rainfall (or average winter and summer) with wheat (orange bars), barley (blue bars), rice (yellow bars) and maize (grey bars) yields are shown for the four EU sub-regions. Pearson correlation coefficients of correlations are shown in the *y*-axis and temperature or rainfall in the *x*-axis. Only significant correlations ($p < 0.05$) are shown

warmest and driest countries in the SE showed positive correlations between May and June rainfall with wheat, barley and maize yields. However, May temperatures were negatively correlated with barley and maize yields (Figure 3). Barley and maize yields decreased by −140 and −390 kg ha^{-1}, respectively, with an increase of 1°C in May (Table S2). Analysis of the correlations in each SE country (Table S3) showed that, in Spain, May and June temperatures were negatively correlated with wheat and barley yields.

Finally, to determine whether increases in temperature occurred in pairs with changes in rainfall, the correlation between the two parameters was calculated, revealing that higher temperatures were associated with decreased rainfall in the summer between 2001 and 2019 in NE, SE and WE (Figure S1).

3.4 | Literature analysis

A literature analysis on wheat, barley, rice and maize yields and climate change (Figure 4) indicated a strong linkage between the co-occurrence of yields of all crops with climate change, growth, temperature, crop management and cropping systems, food security and drought as shown by the size of the circles associated with these keywords in the literature (more than 8000 papers in the Web of Science). The literature analysis also indicated four major clusters of co-occurrence of keywords and these included: cluster 1 (red) included major linkages among ‘Climate change’, ‘Temperature’, ‘Model’ and ‘Food Security’; cluster 2 (green) indicated ‘Yield’, ‘Wheat’, ‘Rice’, ‘drought’, ‘elevated CO2’, ‘Growth’ and ‘Photosynthesis’; cluster 3 (blue) ‘Management’, ‘Nitrogen’ and ‘Cropping Systems’ and cluster 4 (light green) ‘Maize’, ‘Irrigation’, ‘Phenology’, ‘Crop model’ and ‘sowing date’.

4 | DISCUSSION

4.1 | Wheat, barley, rice and maize yield plateaus and progress in Europe

Despite positive progressing yields in many parts of the world, various studies have highlighted the existence of crop yield plateaus in Europe (Moore & Lobell, 2015; Ray et al., 2012; Zhao et al., 2017). Given the diversity of weather conditions in the various EU countries and crop responses, this manuscript aimed at determining the yield progress based on the average yields in all EU countries, by sub-regions (groups of countries in the north, west, east and south) and on a country basis. This evaluation showed that, positive wheat, barley, rice and maize yield progress in Europe was significant as an average of all countries between 1961 and 2019, with rates of 0.05, 0.04, 0.05 and 0.09 $Tha^{-1}year^{-1}$ for the four crops respectively. Positive yield progress is the result of adoption of improved varieties and improved agronomy with better crop and soil management (Graybosch & Peterson, 2010). However, examining yield progress by sub-regions, wheat, barley, rice and maize showed positive yield progress in EE but yield plateaus in WE. Specifically, EE (Figure 1) showed the lowest wheat and barley yields (2.0 and 2.4 Tha^{-1}, respectively) (Table 1) and linear positive yield progress; however, in WE, the yields were the highest (>5 Tha^{-1})

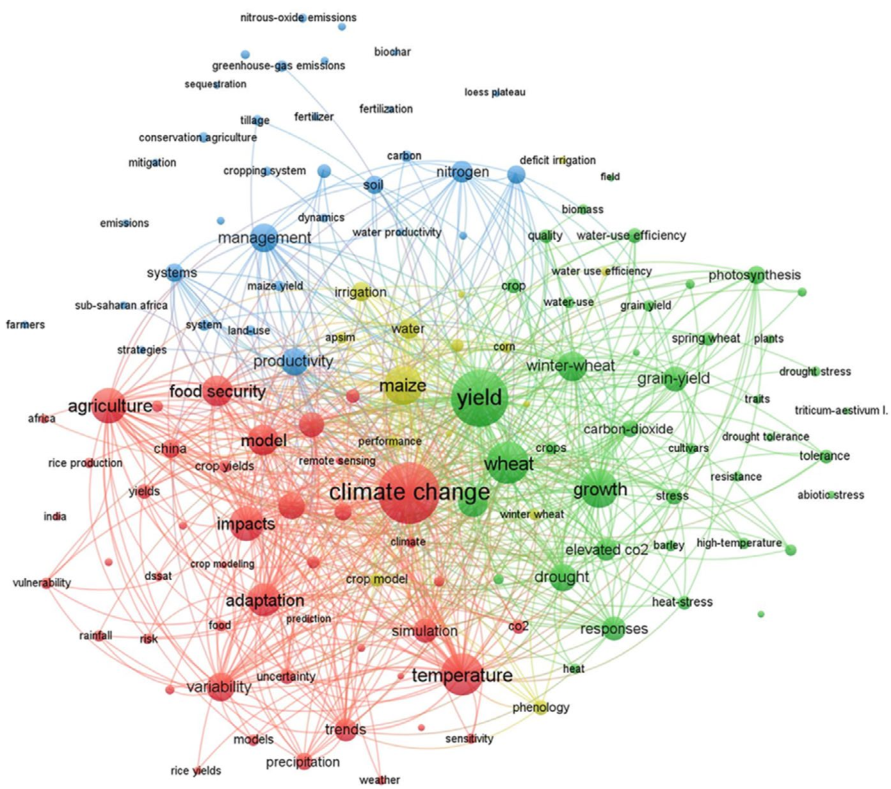

FIGURE 4 Network analysis of available literature (1990–2021) from Web of Science database clustered in three groups (sum of all results from the following search keywords: wheat and yield and ‘climate change’; barley and yield and ‘climate change’; maize and yield and ‘climate change’; rice and yield and ‘climate change’) using VOSviewer (only the first 150 items with the highest-ranking occurrences were selected for network analysis)

but reached plateaus (Figure 1 and Table 1). In SE and NE, the barley and wheat yields, respectively, have been stagnant since 2001. In addition, the rice and maize yields in WE were found to be stagnant, while the yield progress of these two crops was positive and significant in all other EU regions. The yield gaps, defined as the difference between potential and reported yields, have been estimated in several studies (Van Ittersum et al., 2013; Schils et al., 2018). Yield potential assumes optimal crop growth and perfect management, avoiding yield limitations due to nutrient deficiency, drought, extreme high or low temperatures and the impact of weeds, pests and diseases. The results presented herein suggest that yield plateaus occur in countries with narrower yield gaps (western and northern countries), where yields are closer to yield potential (20–40%) (Schils et al., 2018). In contrast, the linear positive yield progress reported in EE and SE, where yield gaps are higher (50–60%), suggested ample scope for further yield increase, providing the environment and management practices were favourable. In the following sections, how temperature and rainfall patterns may contribute to yield responses is discussed (Sections 4.2–4.4).

4.2 | Temperature and rainfall effects on wheat yields in EU

Although the dissection of yield data is difficult to achieve, given all the above-mentioned parameters potentially affecting final yields, the present study attempted to analyse the effects of temperature and rainfall to identify hotspot regions where global warming may lock yield potential even when yield gaps are high. The results presented herein show that, in the past 19 years, temperature has been increasing in all EU sub-regions and rainfall has been stagnant in SE and WE, decreasing in EE and increasing in NE (Figure 2). This has been well reported in the Intergovernmental Panel on Climate Change (IPCC, 2007). Various research groups have indicated their concerns regarding the impact of rising temperatures on agriculture, which has the potential to significantly reduce global yields (Moore & Lobell, 2015; Peng et al., 2004; Zhao et al., 2017). Some studies have used modelling and highly sophisticated calculations to show the negative impacts of rising temperatures on crops over time owing to the difficulties in finding direct correlations among such complex traits. However, recent studies have tested the impacts of high temperatures in the field in Schittenhelm et al. (2020), with an average grain yield reduction of 57.3% compared to a non-stressed control. It is particularly challenging to separate the effects of temperature and drought given that the increase in temperature results in increased evapotranspiration (Feldhake & Boyer, 1986) and more intense drought episodes according to the temperature range.

Before analysing the effects of temperature on the results presented herein, it is important to understand that wheat and barley cultivation varies across the EU, and the effects of temperature will change depending on the region and type of germplasm. For instance, winter wheat and barley are the most common wheat and barley types in Europe; these have considerable requirements for entry into the reproductive stage, namely low temperature accumulation and photoperiod sensitivity (Curtis et al., 2002). Winter wheat and barley are sown in autumn and harvested in August. Spring types do not require low temperatures and are generally photoperiod insensitive; they are sown in the autumn and harvested in July in warmer regions (SE) and sown in the spring and harvested in late summer in cooler northern regions (NE countries), where even winter cereals cannot survive extreme winter cold temperatures (Roberts et al., 1988). With regards to summer crops, rice and maize are cultivated in the summer across the entire EU and are cold sensitive, depending on the country, rainfall availability and distribution.

Despite increasing temperatures in temperate and cold NE and increasing rainfall in NE countries, wheat yields have been stagnant (Figure 1 and Table 1). In WE countries, neither rainfall nor temperature has any historical effect on wheat yield, except in Austria, Germany and the Netherlands (correlations between July temperatures and wheat yields were −0.46, −0.64 and −0.64, respectively) (Table S1). In cooler NE countries, increasing summer temperatures have negatively impacted wheat yields in this region, with decreases of −450 kg ha^{-1} per 1°C increase, despite the positive effects of overall rainfall, winter rainfall and winter temperatures (Table S2). Potentially, higher summer temperatures shorten the grain filling period, halting grain yields (Impa et al., 2021; Schittenhelm et al., 2020). Wheat is sown in April and harvested in September in many parts of NE producing short wheat crop cycles (not more than 5 months in contrast to 9 months in SE and WE), and wheat cycles may become even shorter with the temperature increase, accelerating grain filling even more and reducing final yields. WE winter wheat is the most common cropping system, with autumn sowing; however, in NE spring, wheat is the most common, where cold tolerance, but not heat tolerance, has historically been a highly rated and desirable trait. Consequently, with increasing temperatures, and considering that wheat cultivars in these regions are sensitive to higher temperatures or less adapted to the changing climate (see Mäkinen et al., 2018), wheat yields have become stagnant.

In EE, where winter temperatures are the lowest in the EU (Figures 2 and 3), temperature increases have significantly contributed to increasing wheat yields (Figure

3 and Table S2), most likely due to there being better temperatures for photosynthesis and crop development. Previous studies have shown the dependence of photosynthetic parameters Vcmax and Jmax on leaf temperature (Farquhar et al., 1980; Harley & Tenhunen, 1991), increasing to maximum rates at the optimal leaf temperature and then declining again. However, this positive effect of temperature may soon disappear if rainfall continues to decrease at the current pace of −1.3 mm $year^{-1}$ in EE countries, which will result in more frequent drought episodes. In contrast, in already warm SE countries, temperature had a positive effect on wheat yields in April and rainfall positively impacted yields in May and June, highlighting the importance of rainfall in sustaining wheat yield progress in SE (Figure 3 and Table S2). Moreover, wheat yields in Spain, where yields were stagnant, were negatively affected by temperature in March, May and June, with significant correlations between temperatures in those months and wheat yield at $r = -0.48$, −0.49 and −0.67, $p < 0.005$ (Table S3). Higher temperatures in April are potentially an indication of decreased frost and cold damage during the onset of the sensitive reproductive phase in SE countries. However, this was not the case in Spain, where wheat yields were found to be collapsing (Table S1) due to increasing temperatures and more frequent drought episodes during grain filling.

In conclusion, stagnant wheat yields in WE (only Austria, Germany and the Netherlands), NE countries and Spain were associated with increased summer temperatures. As a result, new varieties that are able to maintain longer grain filling periods, despite temperature increases in all EU regions, are needed. However, in EE and in some SE countries, temperatures have been more favourable for wheat growth and photosynthesis, supporting yield progress, provided that rainfall does not decrease.

4.3 | Temperature and rainfall effects on barley yields in EU

As shown for wheat, barley yields have been stagnant in WE, which is not explained by temperature (Table S3) or by rainfall. Stagnant barley yields in SE were explained by increasing temperatures in May, with a loss of 140 kg ha^{-1} per 1°C increase in May (Table S2). In Spain, stagnant barley yields were associated with increased temperatures in March, May and June, with $r = -0.60$, −0.59 and −0.63 respectively (Table S3). Moreover, in years with more rainfall in May, barley yields were higher in SE, indicating that barley in SE is particularly sensitive to drought periods during this month. Although rainfall in SE did not change over the past 19 years, a significant correlation between yield and rainfall indicated sensitivity in low rainfall years. The negative impact of May–June temperatures and drought effects in years when rainfall is low (heading-anthesis time starts in May–June) observed in the historical data analysed here support the predictions reported by Semenov and Shewry (2011), who used modelling to find that the risk of heat stress around flowering would increase. Stagnant barley yields in SE are likely to be caused by less than favourable temperatures and rainfall (Table S2) for the reproductive stages, shortened grain filling periods, decreased photosynthesis and photo assimilates for grain filling (Schittenhelm et al., 2020). Moreover, increasing temperatures results in increased evapotranspiration and are associated with decreased rainfall (Figure S1), resulting in more frequent drought episodes during grain filling that together negatively impact barley yields.

With regards to the positive barley yield progress observed in EE and NE (Figure 1), the implication of increasing winter temperatures was demonstrated by positive associations between yield and winter temperatures in those regions (Figure 3 and Table S2). As explained above, increasing temperatures in cold regions have potentially been positively affecting photosynthesis, decreasing frost damage and consequently, increasing barley grain yield. Moreover, increasing temperatures have been supported by increased rainfall in NE countries (Figure 2), which also has benefits in terms of yield progress, if lodging does not become a problem; to support yield progress in NE, it will be important to continue using short and lodging-resistant barley varieties.

4.4 | Temperature and rainfall effects on rice and maize yields in EU

In WE, rice and maize yield progress has been stagnant for the past 19 years (except maize in Belgium and Switzerland, WE) (Figure 1 and Table S1). Similar to wheat and barley in this region, temperature and rainfall did not affect rice yields (Figure 3 and Table S2), and other factors outside the scope of this study contributed to stagnation. However, in maize, increased temperatures in the summer (average summer temperature was negatively correlated with yield) (Figure 3 and Table S2) and years of decreased summer rainfall (rainfall was positively correlated with maize yield) (Figure 3 and Table S2) negatively affected maize yields in WE. Even if overall erratic rainfall patterns prevented the identification of a significant linear response across time (between 2001 and 2019), warmer temperatures are expected to increase water evapotranspiration and increase the probability of drought episodes in years of lower rainfall in these summer crops. This may partially explain the stagnation in maize yields in WE. In this context, optimised irrigation protocols will be needed to ensure that yields are not suppressed by drought episodes as temperatures rise.

Increasing average temperatures in EE between 2001 and 2019 have supported rice and maize yield progress in these regions (Figure 3 and Table S2). Rice and maize are particularly susceptible to low temperatures, particularly during germination and vegetative and reproductive stages (Ben-Haj-Salah, 1995; da Cruz et al., 2013), and increasing temperatures could alleviate this sensitivity and increase overall yields in EE. In SE, rice yield progress was not associated with changes in temperature or rainfall (Figure 3 and Table S2), and other underlying factors could potentially explain the observed yields (agronomy, choice of variety, pest and disease control). Despite the non-significant correlation between rainfall and year in SE countries, maize yield decreased in years with lower summer and total rainfall and with increasing May temperatures (Figure 3 and Table S2). As explained above, increasing temperatures will increase the probability of drought events through increased evapotranspiration, particularly if average temperatures in a particular region are already high, as in SE (Figure 2). These accumulated drought events throughout the maize cycle will affect grain yields, and could explain the slightly lower rates of maize yield progress in SE (0.1 Tha^{-1} as compared to 0.16 and 0.32 in EE and NE, respectively) (Table 1). The rice crop, permanently submerged in water and grown near large sources of water (except in rice sown under dry soil still in lower per cent in the EU), such as rivers, has a much lower probability of experiencing drought events during the growth cycle, and increasing temperature would not result in drought episodes and consequently yields may continue to increase at least if temperatures do not become extreme.

4.5 | Final considerations about temperature and rainfall trends and impact on major crops in the EU

A literature analysis indicated a strong co-occurrence of keywords in research papers including climate change, yields, temperature, growth, crop management, cropping systems, food security and drought. Wheat and maize were the most cited crops followed by rice and barley. This indicates the major dimensions of climate change and impacts on food security that researchers around the world detected in the past decades. Specifically, it has been shown that globally crop production declined in response to climate (Asseng et al., 2015; Lobell et al., 2011). However, a more in-depth analysis of yields in Europe was lacking and herein it is shown that yields are not declining everywhere in the EU. With increased winter and early spring temperatures, crop yields in EE have been favoured and much of the yield progress in Europe is being sustained by eastern countries. However, yield progress is significantly slowing down in WE and this was not explained by changes in temperature or rainfall and other factors may be involved in this response. In SE and NE, positive effects of increasing temperature in early spring were significant for wheat and barley yields, whereas increased May and July temperatures negatively impacted these crops. Higher temperatures in the winter and spring decrease the risk of frost and cold stress promoting photosynthesis, however, in the summer, higher temperatures shorten the crop cycle and reduce grain and yield formation. It is concluded that temperature in some SE and NE countries is already preventing positive yield progress but not yet in Eastern Europe.

Knowledge about novel strategies to extend grain filling and maintain photosynthesis with increasing temperatures and drought is scarce in the available literature and may open new opportunities to break the yield barrier associated with climate change. Another consequence of higher temperatures is the increase in evaporative demand and water requirements to sustain crop productivity particularly affecting crop yields in countries with lower rainfall. Maize yields were correlated with summer rainfall in SE, a region where summer rainfall is limited and where maize yields depend on irrigation. Smart irrigation systems and water management strategies are required, and the literature analysis indicated relatively low research efforts in this direction. The potential increase in temperature and drought events will require important efforts from farmers to adopt new drought- and heat-tolerant wheat, barley and maize varieties (released through breeding). Moreover, there are potentially important crop management restrictions in all EU countries, where inputs, particularly fertilisers and pesticides, are high and require regulatory policies to reduce their environmental impact. To counteract the effects of low inputs and increase resilience, efforts are needed to increase crop diversity (Hertel et al., 2021), crop disease and pest resistance, and more nutrient-efficient varieties to ensure that yields continue to increase. Finally, the interplay among genetic adaptation, crop cycle duration, sowing dates and smart irrigation systems is likely to require constant local adjustments and thorough testing to identify optimal parameters and maximise yields regionally.

ACKNOWLEDGEMENTS

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. This research was funded by the projects RTA2015-00072-C03-01 from the Spanish Ministry of Economy and Competitiveness (http://www.mineco.gob.es). The author thanks the Spanish Ministry of Economy and Competitiveness and the CERCA Programme/Generalitat de Catalunya (http://cerca.cat/) for supporting this research.

REFERENCES

Aisawi, K. A. B., Reynolds, M. P., Singh, R. P., & Foulkes, M. J. (2015). The physiological basis of the genetic progress in yield potential of CIMMYT spring wheat cultivars from 1966–2009. *Crop Science*, *55*, 1749–1764.

Asseng, S., Ewert, F., Martre, P., Rötter, R. P., Lobell, D. B., Cammarano, D., Kimball, B. A., Ottman, M. J., Wall, G. W., White, J. W., Reynolds, M. P., Alderman, P. D., Prasad, P. V. V., Aggarwal, P. K., Anothai, J., Basso, B., Biernath, C., Challinor, A. J., De Sanctis, G., … Zhu, Y. (2015). Rising temperatures reduce global wheat production. *Nature Climate Change*, *5*, 143–147.

Ben-Haj-Salah, H., & Tardieu, F. (1995). Temperature Affects Expansion Rate of Maize Leaves without Change in Spatial Distribution of Cell Length (Analysis of the Coordination between Cell Division and Cell Expansion). *Plant Physiology*, *109*, 861–870. https://doi.org/10.1104/pp.109.3.861

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F. X., & Huarda, F. (2010). Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crops Research*, *119*, 201–212. https://doi.org/10.1016/j.fcr.2010.07.012

Crespo-Herrera, L. A., Crossa, J., Huerta-Espino, J., Vargas, M., Mondal, S., Velu, G., Payne, T. S., Braun, H., & Singh, R. P. (2018). Genetic gains for grain yield in CIMMYT's semi-arid wheat yield trials grown in suboptimal environments. *Crop Science*, *58*, 1890–1898. https://doi.org/10.2135/cropsci2018.01.0017

Curtis, B. C., Rajaram, S., & Macpherson, H. G. (Eds.) (2002). *Bread wheat: Improvement and production*. Food and Agriculture Organization of the United Nations.

da Cruz, R. P., Sperotto, R. A., Cargnelutti, D., Adamski, J. M., Freitas Terra, T., & Fett, J. P. (2013). Avoiding damage and achieving cold tolerance in rice plants. *Food and Energy Security*, *2*, 96–119. https://doi.org/10.1002/fes3.25

Farquhar, G. D., Caemmerer, S., & Von Berry, J. A. (1980). A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species. *Planta*, *149*, 78–90. https://doi.org/10.1007/BF00386231

Feldhake, C. M., & Boyer, D. G. (1986). Effect of soil temperature on evapotranspiration by C3 and C4 grasses. *Agricultural and Forest Meteorology*, *37*, 309–318. https://doi.org/10.1016/0168-1923(86)90068-7

Graybosch, R. A., & Peterson, C. J. (2010). Genetic improvement in winter wheat yields in the great plains of North America, 1959–2008. *Crop Science*, *50*, 1882–1890. https://doi.org/10.2135/cropsci2009.11.0685

Harley, P. C., & Tenhunen, J. D. (1991). Modeling the photosynthetic response of C3 leaves to environmental factors. In K. J. Boote, & R. S. Loomis (Eds.), *Modeling Crop Photosynthesis—From Biochemistry to Canopy* (pp. 17–39). Crop Science Society of America, Inc. and American Society of Agronomy, Inc.

Hatfield, J. L., & Prueger, J. H. (2015). Temperature extremes: Effect on plant growth and development. *Weather and Climate Extremes*, *10*, 4–10. https://doi.org/10.1016/j.wace.2015.08.001

Hertel, T., Elouafi, I., Tanticharoen, M., & Ewert, F. (2021). Diversification for enhanced food systems resilience. *Nature Food*, *2*, 832–834. https://doi.org/10.1038/s43016-021-00403-9

Impa, S. M., Raju, B., Hein, N. T., Sandhu, J., Prasad, P. V. V., Walia, H., & Jagadish, S. V. K. (2021). High night temperature effects on wheat and rice: Current status and way forward. *Plant, Cell & Environment*, *44*, 2049–2065.

IPCC (2007). Summary for policymakers. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 7–22). Cambridge University Press.

Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science*, *333*, 616–620. https://doi.org/10.1126/science.1204531

Lopes, M. S., Reynolds, M. P., Manes, Y., Singh, R. P., Crossa, J., & Braun, H. J. (2012). Genetic yield gains and changes in associated traits of CIMMYT spring bread wheat in a "Historic" set representing 30 years of breeding. *Crop Science*, *52*, 1123–1131. https://doi.org/10.2135/cropsci2011.09.0467

Mäkinen, H., Kaseva, J., Trnka, M., Balek, J., Kersebaum, K. C., Nendel, C., Gobin, A., Olesen, J. E., Bindi, M., Ferrise, R., Moriondo, M., Rodríguez, A., Ruiz-Ramos, M., Takáč, J., Bezák, P., Ventrella, D., Ruget, F., Capellades, G., & Kahiluoto, H. (2018). Sensitivity of European wheat to extreme weather. *Field Crop Research*, *222*, 209–217. https://doi.org/10.1016/j.fcr.2017.11.008

Moore, F. C., & Lobell, D. B. (2015). Climate fingerprint on European crop yields. *Proceedings of the National Academy of Sciences of the United States of America*, *112*, 2670–2675.

Peng, S., Huang, J., Sheehy, J. E., Laza, R. C., Visperas, R. M., Zhong, X., Centeno, G. S., Khush, G. S., & Cassman, K. G. (2004). Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Sciences of the United States of America*, *101*, 9971–9975. https://doi.org/10.1073/pnas.0403720101

Ray, D., Ramankutty, N., Mueller, N., West, P. C., & Foley, J. A. (2012). Recent patterns of crop yield growth and stagnation. *Nature Communications*, *3*, 1293. https://doi.org/10.1038/ncomms2296

Roberts, E. H., Summerfield, R. J., Cooper, J. P., & Ellis, R. H. (1988). Environmental control of flowering in barley (*Hordeum vulgare* L). I. Photoperiod limits to longday responses, photoperiod-insensitive phases and effects of low-temperature and short-day vernalization. *Annals of Botany*, *62*, 127–144. https://doi.org/10.1093/oxfordjournals.aob.a087644

Saini, H. S., & Westgate, M. E. (1999). Reproductive development in grain crops during drought. *Advances in Agronomy*, *68*, 59–96.

Schils, R., Olesen, J., Kersebaum, K., Rijk, B., Oberforster, M., Kalyada, V., Khitrykau, M., Gobin, A., Kirchev, H., Manolova, V., Manolov, I., Trnka, M., Hlavinka, P., Paluoso, T., Peltonen-Sainio, P., Jauhiainen, L., Lorgeou, J., Marrou, H., Danalatos, N., … van Ittersum, M. (2018). Cereal yield gaps across Europe.

European Journal of Agronomy, *101*, 109–120. https://doi.org/10.1016/j.eja.2018.09.003

Schittenhelm, S., Langkamp-Wedde, T., Kraft, M., Kottmann, L., & Matschiner, K. (2020). Effect of two-week heat stress during grain filling on stem reserves, senescence, and grain yield of European winter wheat cultivars. *Journal of Agronomy and Crop Science*, *208*, 722–733. https://doi.org/10.1111/jac.12410

Semenov, M., & Shewry, P. (2011). Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe. *Scientific Reports*, *1*, 66. https://doi.org/10.1038/srep00066

van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. *Field Crops Research*, *143*, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., Huang, M., Yao, Y., Bassu, S., Ciais, P., Durand, J.-L., Elliott, J., Ewert, F., Janssens, I. A., Li, T., Lin, E., Liu, Q., Martre, P., Müller, C., … Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 9326–9331. https://doi.org/10.1073/pnas.1701762114

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Lopes, M. S. (2022). Will temperature and rainfall changes prevent yield progress in Europe? *Food and Energy Security*, 00, e372. https://doi.org/10.1002/fes3.372