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Priority for climate adaptation measures in European crop production systems

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A R T I C L E I N F O

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A B S T R A C T

To date, assessing the adaptive measures to climate change effects on cropping systems have generally been based on data from field trials and crop models. This strategy can only explore a restricted number of options with a limited spatial extent. Therefore, we designed a questionnaire that incorporated both qualitative and quantitative aspects of climate change adaptation in the agricultural sector. The questionnaire was distributed to experts from 15 European countries to map both the observed and planned climate adaptive measures in general and for five major crops (wheat, oilseed rape, maize, potato, and grapevine) in six environmental zones (EnZs) across Europe. In northern Europe, changed timing of field operations and introduction of new crops and cultivars were the already observed as the main adaptations to a longer growing season and reduced low-temperature stress under climate change. Farmers in central and southern Europe were mainly changing water and soil management as well as adopting drought-tolerant cultivars to cope with increasing

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evapotranspiration and higher variability and lower predictability of rainfall. Crop protection, crop insurance, and early warning/forecast systems were considered effective ways to reduce the economic losses from increased climate-related risks and extremes. The risks and associated adaptation measures vary for different crops in different EnZs. Across Europe, changes in field operation practices, fertilisation regime, crop protection, and cultivar selection are expected to be the most prominent adaptive measures under future projected climate change. In southern and central Europe, improved irrigation systems, changing cropping systems, and revised environmental regulations and subsidy schemes are being introduced as part of adaptation planning due to the projected warmer and drier climate. In northern Europe, there are also considerations of changing landscape and environmental regulations to cope with increasing rainfall variability and changing cropping practices due to longer growing seasons. The thorough understanding of the observed and foreseen adaptations in the different zones will be helpful for supporting decision making at both farm and policy levels across Europe.

1. Introduction

As one of the world's largest and most productive suppliers of food and fibre, Europe accounted for 17.6% of the global cereal production during 2014–2018, and the average yields in EU countries were 6.8% higher than the world average in the same period, in particular in western Europe (FAOSTAT, 2019). Apart from supporting food security goals, agriculture is also an important sector in Europe providing employment opportunities to rural populations (Iglesias and Garrote, 2015), and it is a major player for the European landscapes affecting biodiversity, environment (i.e., air, soil, water pollution and greenhouse gas emissions), and the sustainable food production (European Commission, 2020). These services are currently under threat by climate change, and adaptation measures of the agricultural sector to climate change are therefore increasingly included as part of policy concerns (EEA, 2019).

1.1. Climate change in Europe

The observed warming trend (+0.9 °C from 1901 to 2005) in Europe is well established (Alcamo et al., 2007), and during 2006–2015, the land temperatures were ~1.5 °C warmer than the pre-industrial level (EEA, 2017). The warming climate has increased the frequency, intensity, and duration of heatwaves over Europe (Beniston et al., 2007; Lorenz et al., 2019). The average temperature has continued to increase more than the global average temperature increase, with regionally and seasonally different rates of warming being greatest at high latitudes in northern Europe (EEA, 2017; Kovats et al., 2014; Trnka et al., 2011). In contrast, precipitation trends are spatially more variable, and precipitation has increased in most of the Atlantic and northern Europe in winter, but has decreased in most of southern Europe in summer (EEA, 2017). Furthermore, the probability of extreme weather events in Europe has substantially increased as a consequence of anthropogenic climate change (EEA, 2017; Naumann et al., 2015).

1.2. Climate change impacts on agricultural systems

Changes in climatic conditions have a considerable impact on European agricultural land use and management (Olesen and Bindi, 2002). For example, agricultural systems in Northern Europe are projected to be further exposed to increased temperature, especially during winter, and to increased precipitation levels, as well as to an increase in variability of temperature and precipitation and more frequent occurrence of extreme weather events, such as heatwaves, heavy rainfalls, winter storms, and drought (Beniston et al., 2007; Bindi and Olesen, 2011; Ceglar et al., 2018; Himanen et al., 2013; Olesen et al., 2011; Schaap et al., 2011; Trnka et al., 2014; Uleberg et al., 2014). By the end of the 21st century, extreme temperatures are projected to increase more rapidly than the intensity of more moderate temperatures over the continental interior due to increases in temperature variability (Beniston et al., 2007; Ceglar et al., 2018; Juhola et al., 2017; Spinoni et al., 2018).

In general, climate change is expected to affect both regional and global food production through changes in overall agro-climatic conditions (Trnka et al., 2011). In Europe, cropping systems have already been affected by climate change (Olesen et al., 2011; Peltonen-Sainio et al., 2010), which influenced the tendency towards stagnation of cereal grain yields (Brisson et al., 2010) and increased yield variability (Agnolucci and De Lipsis, 2020). Warming has prolonged the growing season and frost-free period for crops across all of Europe since the 1980s (Ceglar et al., 2018; EEA, 2017). The delayed end of the growing season by 8.2 days was more significant than the advanced start of the season (Jeong et al., 2011), and the length of the frost-free period has increased more in northern and eastern parts than in the western and southern parts (Ceglar et al., 2018; EEA, 2017). Recent warming in Europe has advanced the crop phenology and led to the northward expansion of the crop cultivation areas during the last 50 years (Ceglar et al., 2018; Chmielewski et al., 2004; Martin et al., 2017; Siebert and Ewert, 2012).

1.3. Observed effects of climate change on crop yield

Negative effects of climate change on cereal crop production have been reported in most of the countries worldwide, as well as for various European countries (Peltonen-Sainio et al., 2010), including decreased yields and increased yield variability (Hawkins et al., 2013; Olesen et al., 2011). Based on the long-term national and/or regional yield datasets and meteorological records, high precipitation and elevated temperatures during the grain-filling stage had harmful effects for cereals and rapeseed yields in many European countries (Peltonen-Sainio et al., 2010). For Germany, Bönecke et al. (2020) identified high temperatures during grain filling and dry spells during the late vegetative phase as main drivers for negative climate impacts on wheat (*Triticum aestivum* L.) yields, especially on soils with low water holding capacity. In Italy and southern-central Europe, the potential crop yields of potato (*Solanum tuberosum* L.), wheat, maize (*Zea mays* L.) and barley (*Hordeum vulgare* L.) significantly decreased over the period 1976–2005 owing to changes in temperature and radiation (Supit et al., 2010). In north-east Spain, the grape yields have been declining because of increasing water deficits since the 1960s (Camps and Ramos, 2012).

Climate change may also increase the spread of weeds, insects, pests, and diseases to the new areas (Roos et al., 2011), and the frequency of extreme events with deteriorating agro-climatic conditions may also lead to higher inter-annual variability in crop yield (Trnka et al., 2011). For example, droughts and heatwaves affected crop production in large areas of southern and central Europe in 2003 and 2007 (Peltonen-Sainio et al., 2010). In 2018, drought conditions in central and northern Europe caused yield reductions of up to 50% for the main crops (Toreti et al., 2019). A wet start and end of the season was identified as the main yield affecting weather extremes for potato in the Netherlands (van Oort et al., 2012). In addition, warm and wet conditions can have large impacts on fungal disease development, affecting high-value crops like onion (Schaap et al., 2013), potato (Runno-Paurson et al., 2019c), and different cruciferous oilseed crops (Runno-Paurson et al., 2021). Trends of increasing crop water deficit, i.e. crop water demand exceeding average rainfall, for maize were found in large parts of southern and eastern Europe during 1995–2015 (EEA, 2017).

At the same time, climate change has also shown positive effects on crop production. The extended growing seasons may allow for the introduction of new crop species in the areas limited by low temperature or shorter growing seasons, e.g. potato, sugar beet, maize (Gregory and Marshall, 2012; Peltonen-Sainio et al., 2011, 2010; Romaneckas et al., 2020), and sweet potato, proso millet and hemp (Lääniste et al., 2019; Runno-Paurson et al., 2019a, 2019b). Increasing yields in wheat and maize have also been reported in parts of the United Kingdom and northern Europe, especially because of better growing conditions for winter wheat (Olesen et al., 2011; Supit et al., 2010) and longer growing season for maize (Elsgaard et al., 2012). Thus, impacts of climate change on crop yield will be unevenly distributed over European regions, differently affecting climate-sensitive crop production systems and associated industries and putting additional pressures on the existing socio-ecological structures and functions (Biesbroek et al., 2010; Eakin and Luers, 2006; Folke, 2006; Folke et al., 2005).

1.4. Projected effects of climate change on crop yield

Over the next decades, the warming trend in Europe is projected to lead to climatic conditions that significantly differ from contemporary climate (Jacob and Podzun, 2010). A warming climate is expected to advance the start date of the frost-free period by 5–10 days by 2030 and 10–15 days by 2050 (Ceglar et al., 2018; Trnka et al., 2011), and for the majority of Europe, the growing season will be prolonged by 1.5–2 months in the late 21st century (Ruosteenoja et al., 2015). In northern Europe, crop production will benefit through the introduction of new crops that require higher growing degree days for maturation (Elsgaard et al., 2012; Ruosteenoja et al., 2020). High latitude areas may even exploit double-cropping of e.g., primary and green-manuring cover crops in the future (Peltonen-Sainio et al., 2018), as higher temperature is projected to advance the flowering dates and lead to a shortening of crop growth duration in cereal crops (Olesen et al., 2012; EEA, 2017). Additionally, the increased likelihood and severity of extreme weather events will considerably enhance the risk of crop failure, result in higher inter-annual yield variability and constitute a challenge for crop management (Commission of the European Communities, 2009; Eitzinger et al., 2013; Trnka et al., 2011). For example, rainfed agriculture is likely to face more climate-related risks, although the agro-climatic indicators will probably remain at a level that should permit rainfed crop production (Toreti et al., 2019: Trnka et al., 2011).

Modelling suggests that climate change may affect crops in central Europe very differently and that site conditions will determine whether yields will increase or decrease (Kersebaum and Nendel, 2014; Webber et al., 2020). Other model-based studies suggest that by the mid of the 21st century, the average heat stress may not increase for either maize or winter-sown wheat in Europe, while drought stress intensifies for maize only (Webber et al., 2018). In low-yielding years, drought stress persists as the main driver of losses for both crops, with elevated CO_2 offering only limited yield benefit in these years. Most projections are based on crop modelling, considering only processes that can be simulated and are well understood. The effects of extreme events, including pests and diseases, are often ignored in such studies, while they may greatly affect projected impacts and required adaptation measures (Reidsma et al., 2015; Schaap et al., 2013).

1.5. Climate change adaptive measures

The need to cope with increasing global food demands while also meeting other sustainability targets in terms of reducing reliance on non-renewable resources, environmental pressures, and greenhouse gas emissions requires that agriculture successfully adapts to the changing climate (Guan et al., 2017; Iglesias and Garrote, 2015). Effective adaptation may help overcome the negative effects of climate change and exploit new opportunities (Bruin et al., 2009; Biesbroek et al., 2010). Reidsma et al. (2010) showed that impacts of climate change and variability are not as severe as projected by crop models, suggesting that adaptation by European farmers have modified the predicted impacts. A meta-analysis with a new data set of more than 1700 published simulations around the world showed that crop-level adaptive measures increase simulated yields by an average 7–15%; such adaptation include changes in cultivars, planting times, irrigation and crop residue management (Challinor et al., 2014). In the Netherlands, the impact of farm-level adaptation including changing crops, was in a similar range as crop-level adaptation (Reidsma et al., 2015). In Europe, average farm profits were simulated to increase modestly (1.5%) with adaptation, but could decline by 2.3% without adaptation to climate change; these predictions were based on both process-based models and statistical techniques (Moore and Lobell, 2014).

Among all the adaptation measures, the greatest benefits may result from the development of new, adapted crop cultivars (Lobell et al., 2008; Rosenzweig and Parry, 1994). New varieties with better environmental tolerances and resource use efficiency (e.g. water, nitrogen, radiation) may better adapt to the increased abiotic (e.g. heat and drought) and biotic (e.g. weeds, pest, and diseases) stresses under climate change (O'Leary et al., 2015; Semenov et al., 2014; Tanaka et al., 2015). Coupled with adapted sowing date, seeking crops or varieties with a better match of phenology is another recommendation to deal with the shortening of crop cycle duration and occurrence of extreme events during the sensitive periods (Ruiz-Ramos et al., 2018; Parent et al., 2018) and make better use of the available climate resources (EEA, 2017). The use of earlier heading and more heat-tolerant wheat cultivars appears to be a promising adaptation strategy in France (Gouache et al., 2012). In Finland, even very late maturing wheat cultivars ripen too early to fully benefit from the longer growing seasons in the future (Peltonen-Sainio et al., 2018). Regarding field production practices and technological developments, adoption of sowing dates (Kaukoranta and Hakala, 2008), adjustments in crop rotations (Nendel et al., 2014), soil management for better water use (Olesen et al., 2011; Peltonen-Sainio et al., 2021a), irrigation management (Nendel et al., 2014; Tanaka et al., 2015; Peltonen-Sainio et al., 2021b), and expansion of supplementary irrigation (e.g. limited to one single event) to selected areas (Ruiz-Ramos et al., 2018) were suggested in Europe.

The relative importance of different adaptation measures differs between crops in different environmental regions (González-Zeas et al., 2014; Holzkämper et al., 2015; Iglesias et al., 2012; Nendel et al., 2014; Knox et al., 2016; Olesen et al., 2011). For example, an empirical analysis shows that adaptation has the potential to reduce adverse impacts on maize yields by 87%, but only by 7% and 31% for wheat and barley yields, respectively, which results from several factors including more extensive irrigation of maize or a wider range of cultivars in use across Europe (Moore and Lobell, 2014). Main climate risks differ among crops, just as the economic damage, and effectiveness of adaptation measures, influencing the cost-effectiveness of different adaptation measures (Schaap et al., 2013). Furthermore, different adaptation measures often need to be combined to overcome the detrimental effect of the complex interactions of climate change (Ruiz-Ramos et al., 2018). Therefore, effective adaptation strategies should take into account the local environment and agricultural productive conditions. However, there remains considerable uncertainty about impacts and the effectiveness of adaptations (Challinor et al., 2014; Howden et al., 2007) as well as farmers' readiness and capability to timely implement the measures (Peltonen-Sainio et al., 2020).

1.6. Objectives of the study

Previous studies of adaptation to climate change for cropping systems in Europe have mostly only considered the contributions of specific production practices or technologies based on results from crop modelling, field experiments and analyses of farm surveys. There has been little effort in mapping the ongoing or considered adaptation efforts in the crop production across Europe, with few national-level exceptions (Schaap et al., 2013; Peltonen-Sainio et al., 2020, 2021a). In our previous studies (Olesen et al., 2011; Trnka et al., 2011), we assessed the agro-climatic conditions and the impacts of climate change on crop systems across Europe. As follow-up on these studies, we compiled a comprehensive set of qualitative and quantitative questions addressing the ongoing efforts to cope with climate change. The questionnaire was distributed to agrometeorological and agronomic experts, agro-engineering experts, farmers, experts in private sectors, regional administrators and social scientists in each European environmental zone. We aimed to map the observed and planned adaptations in crop and soil management for major crops in Europe and assess their attribution to climate change.

2. Materials and methods

2.1. Study areas

As the climate conditions do not follow national boundaries, European Environmental Zones (EnZs) were used for spatial disaggregation in our study. Metzger et al. (2005) defined 13 EnZs based on 20 variables. To make the classification more suitable for agriculture, we merged some of the zones with similar crop production. The Anatolian (ANA) and Alpine North (ALN) zones only occur in Turkey and northern parts of Europe, and both zones were excluded from the study, resulting in six agro-EnZs used in this study (Fig. 1).

2.2. Data

Five major crops, wheat, maize, oilseed rape, potato, and grapevine, which represent widely grown cereals, oilseed crops, tuber crops and fruits in Europe, were included in the study. Country-level statistical data of planting areas of the major crops were downloaded from FAOSTAT database for the six studied zones. Depending on the data availability, planting areas were analyzed during the period of 1992–2016. To calculate the change of planting area in each zone, we assumed that the five major crops were planted evenly throughout each country. Therefore, annual planting areas of the five major crops were calculated in each zone as:

$$PA_i = \sum_{j=1}^{n} \left(PA_{ij} \times \frac{LA_{ij}}{LA_j} \right) \quad (1)$$

where PA_i is the planting area in agro-EnZ i (10^6 ha); PA_{ij} is the planting area in country j in agro-EnZ i (10^6 ha); LA_j is the land area in agro-EnZ i (10^6 ha); LA_{ij} is the land area in country j in agro-EnZ i (10^6 ha); n is the

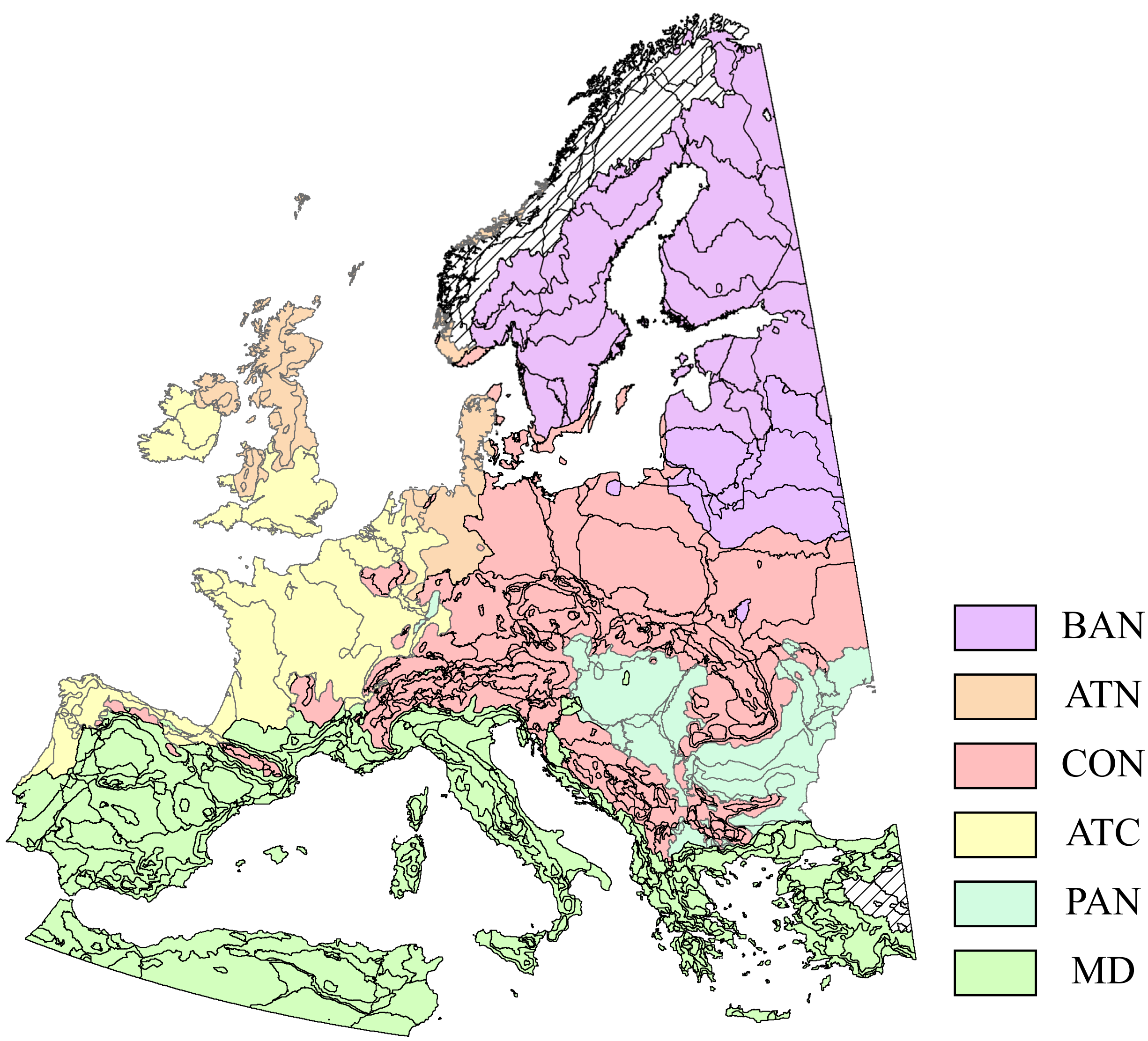

Fig. 1. Agro-environmental zones in Europe (BAN: Boreal and Nemoral, ATN: Atlantic North, CON: Continental and Alpine South, ATC: Atlantic Coast, PAN: Pannonian, MD: Mediterranean).

number of countries in each agro-EnZ.

To gather information about the observed and foreseen changes of agriculture comparing the periods of 1991–2000 with 2012–2016 and their attributions to climate change in each environmental zone in Europe, a set of qualitative and quantitative questions were distributed to experts across Europe. These experts covered agro-meteorological and agronomy researchers knowledgeable on national and regional effects of climate change on crops and adaptations. The experts were asked to base their judgement on objective evidence (e.g., papers, reports and observations). The questionnaires provided detailed evaluations on:

(1) General observed changes in cropping practices and climate change attributions (scale in Table 1).
(2) Specific observed changes in crop practices and climate attributions for five major crops (scale in Table 1).
(3) Possible adaptation options in the future (scale in Table 1).

In the questionnaires, the experts were first asked to assess the already observed changes for the agricultural cropping systems in general and for the five major crops using the predefined scale in Table 1. Cropping systems are not only affected by climate change, but also by socioeconomic conditions, agricultural inputs, and policy (Reidsma et al., 2015; Yin et al., 2016). Therefore, we subsequently asked each expert to estimate to which extent the change can be attributed to climate change using the scale in Table 1. The score for observed changes indicated which extent of change was observed, while the score for climate change attributes gave the relative contributions of climate change to the observed change. The score for observed changes multiplied by the score for climate change attribution was then used as a measure of the real adaptations to climate change in each zone (Hansen and Stone, 2016). Additionally, planned adaptations that are discussed in the public domain were also collected by the questionnaires.

In accordance with our previous research (Olesen et al., 2011), it was assumed that the adaptations to climate change show a high degree of consistency in homogenous EnZs, but marked differences between zones. In total, we received 58 responses on the questionnaire comprising 15 countries and including contributions from 122 different experts (Supplementary materials). The number of responses received within agro-EnZs is shown in Table 2, and this covers both EU and non-EU countries. Since some of the responses belong to more than one zone or include more than one crop, the summarised number of responses in all the zones in Table 2 were larger than the total number of responses. To reduce the uncertainties caused by disagreements between experts from the same zone, the average scores of zones were sent back to the experts for comments after summarising all responses. If the expert considered that the average scores did not reflect the actual conditions in his/her zone, he/she provided specific adjustments on the scores with explanations.

Table 1
Scales used in the survey for scoring observed change in cropping practices, climate change attributions, and possible adaptation options in the future.

Score	Explanation
Observed change	
NA	Not applicable (e.g. crop not grown)
NI	No information
0	No change
1	Anecdotal evidence of the ongoing adaptation (**Minor**)
2	Evidence of the adaptation being adopted among farmers in the country (**Small**)
3	Pronounced shift substantiated with statistical data (**Moderate**)
4	Significant change occurring across the whole environmental zone (**Significant**)
5	Major change (**Major**)
Climate change attribution	
NA	Not applicable (e.g. crop not grown)
NI	No information
0	Climate change has no effect (caused by other factors)
1	Climate change has a minor influence - change driven by other factors
2	Effect of climate change is pronounced and larger than other factors
3	Mostly or completely caused by climate change
Planned adaptation	
NA	Not applicable (e.g. crop not grown)
NI	No information
0	Not being considered
1	Has been suggested
2	Is being considered by some researchers/advisors
3	Is being recommended in general (policy, advisory, consultants)
4	Is being introduced as part of adaptation planning

3. Results

3.1. Observed changes in planting areas

The trends in planting areas of the five crops differed across the EnZs during the period of 1992–2016 (Fig. 2). In northern Europe (BAN and ATN), the planting areas of wheat and oilseed rape have increased consistently over time, while the area of maize and grape is very limited (less than 0.1×10^6 ha). Meanwhile, the planting areas of wheat, oilseed rape, and maize increased considerably in central Europe (CON, ATN, ATC, and PAN), and the largest increases were found in CON. In contrast, the potato area decreased sharply from 3.8×10^6 ha to 1.9×10^6 ha during 1992–2016 in CON, which was the fastest decline among all EnZs. In southern Europe (MD), planting areas of all the considered crops decreased during 1992–2016, except for oilseed rape.

3.2. General observed adaptations

3.2.1. Timing of field operations

Throughout all six EnZs, minor to moderate adjustments of the timing of field operations was observed, and all these changes are more or less all attributed to climate change (Fig. 3). The most significant changes in field operation timing were advanced sowing dates of spring crops and later sowing dates of winter crops due to the milder winters, or an extended soil water deficit period into autumn, especially in the cooler zone (BAN). In MD, the climate change attribution was higher than for other EnZs, and here changes in sowing dates were mainly due to the need to adapt on a yearly basis to changes in rainfall amount and distribution.

3.2.2. New crops and cultivars

The introduction of new crops and the selection of suitable cultivars are essential for optimising crop production to adapt to climate change and were observed in all six EnZs (Fig. 3). Compared to new crops, the selection of new cultivars changed more significantly in all six EnZs, and new cultivars will, in general, be better adapted to the current environment, including current average climate. Although significant changes in new cultivars were reported across Europe, climate change had only a small effect on changes to new cultivars in BAN and ATC, and a minor influence in the other four EnZs.

3.2.3. Tillage practices

Water-saving cultivation is widely used in PAN and MD to adapt to climate change, where the climate is warm and dry, and the adoption of reduced or no-tillage practices increases the soil water infiltration and retention (Fig. 3). The increased use of these practices was therefore largely attributed to the warmer and drier conditions under climate change. In BAN, CON, and PAN, erosion protection cultivation (e.g., no-till, conservation agriculture, buffer zones, and cover crops) are becoming increasingly popular. However, climate change was estimated to have only minor effects on erosion protection cultivation, since these

Table 2
Countries and the number of responses received within European environmental zones.

Zone	Country	Number of responses per zone						
		General	Wheat	Oilseed rape	Maize	Potato	Grapevine	Plan
BAN-Boreal and Nemoral	Finland, Estonia, Latvia, Lithuania	4	4	4	3	1	1	4
ATN-Atlantic North	Denmark, Germany, the Netherlands,	4	5	2	2	1	0	2
CON-Continental and Alpine South	Austria, Denmark, Germany, Republic of Moldova, Slovakia, Switzerland, Poland, Czech Republic	14	15	16	15	8	4	12
ATC-Atlantic Coast	Belgium, Germany, the Netherlands, Spain	6	6	3	4	2	2	5
PAN-Pannonian	Slovakia, Republic of Moldova, Austria, Czech Republic	6	7	6	7	2	4	7
MD-Mediterranean	Italy, Spain	14	12	0	7	6	5	12

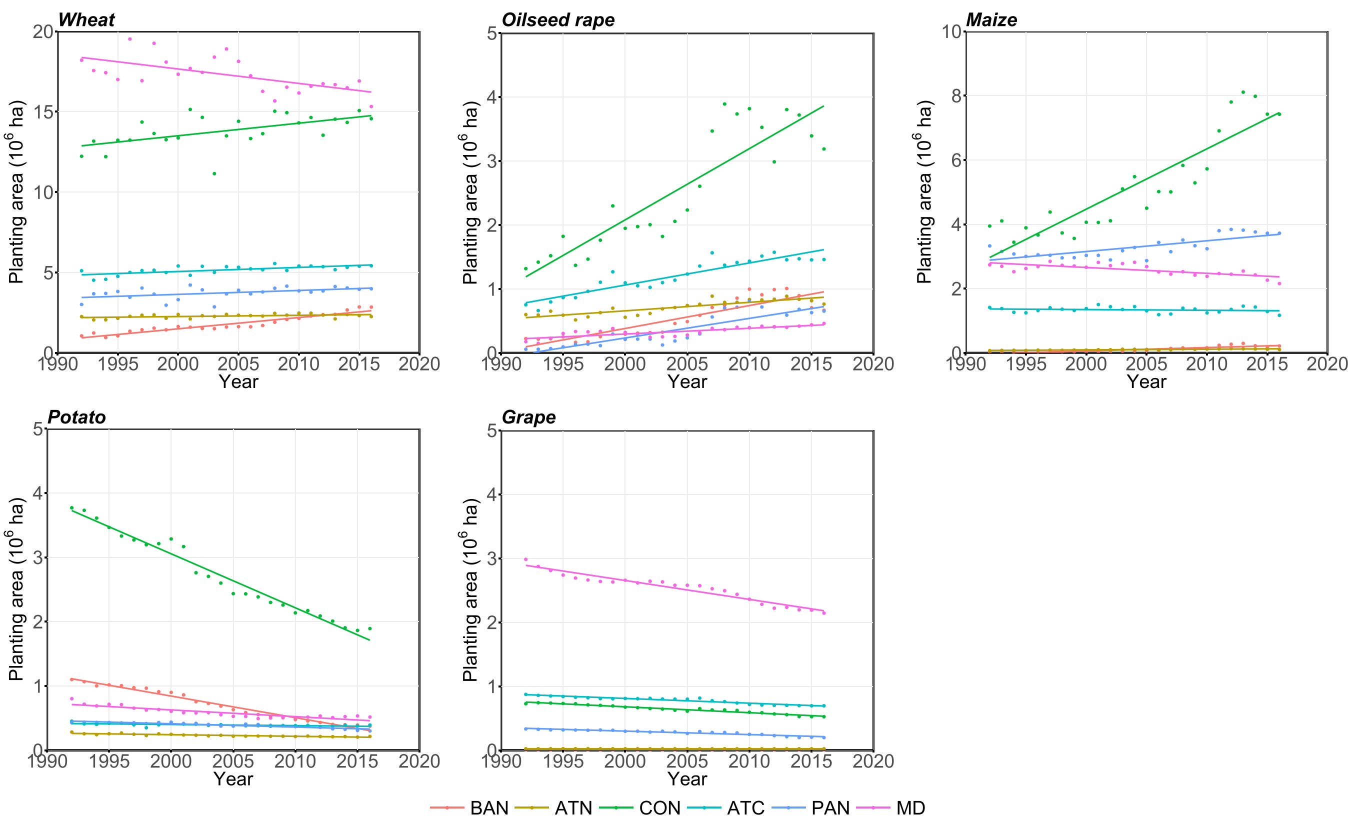

Fig. 2. Planting areas of five major crops (wheat, oilseed rape, maize, potato, and grape) in the six studied environmental zones in Europe for the period 1992–2016 (FAOSTAT database).

are mainly driven by environmental protection issues and associated subsidies.

3.2.4. Water management

In northern Europe (BAN and ATN), there was no observed change in irrigated areas and cultivation of water demanding crops (Fig. 3). Meanwhile, more significant changes in water management are observed in Southern Europe. Both expansion and reduction of irrigated areas in PAN and MD was observed, while the climate change attribution was major to expansion but minor to reduction.

3.2.5. Breeding new cultivars

The observed changes in breeding for changed crop phenology and better drought tolerance are not obvious in northern Europe (BAN and ATN) (Fig. 3). In central and southern Europe (CON, ATC, PAN, and MD), minor to small changes in breeding for changed crop phenology and better drought tolerance were reported. The effects of climate change were perceived pronounced and greater than other factors in PAN and MD. Furthermore, small to moderate changes in breeding for disease and pest resistance happened in all the six EnZs.

3.2.6. Crop protection

According to the respondents, minor to moderate changes in crop protection measures were observed in all six EnZs, while the use of pesticides is facing more strict regulations in European countries (Fig. 3). Climate change had probably no or minor effects on the changes in crop protection, except in MD, while the changes are primarily driven by economic considerations, especially in ATN, CON, ATC, and PAN.

3.2.7. Soil water management

Similar to water management, there is no reported change in soil management for enhanced water harvesting for the high precipitation regions in northern Europe (BAN and ATN) (Fig. 3). However, minor to moderate changes in soil management for water harvesting are reported in central and southern Europe (CON, ATC, PAN, and MD). In BAN, soil management to conserve water (e.g., no-till and residue retention) has become popular, but it is mostly attributed to improved farm management. In some rainfed winter-sown fields in MD, no-tillage was

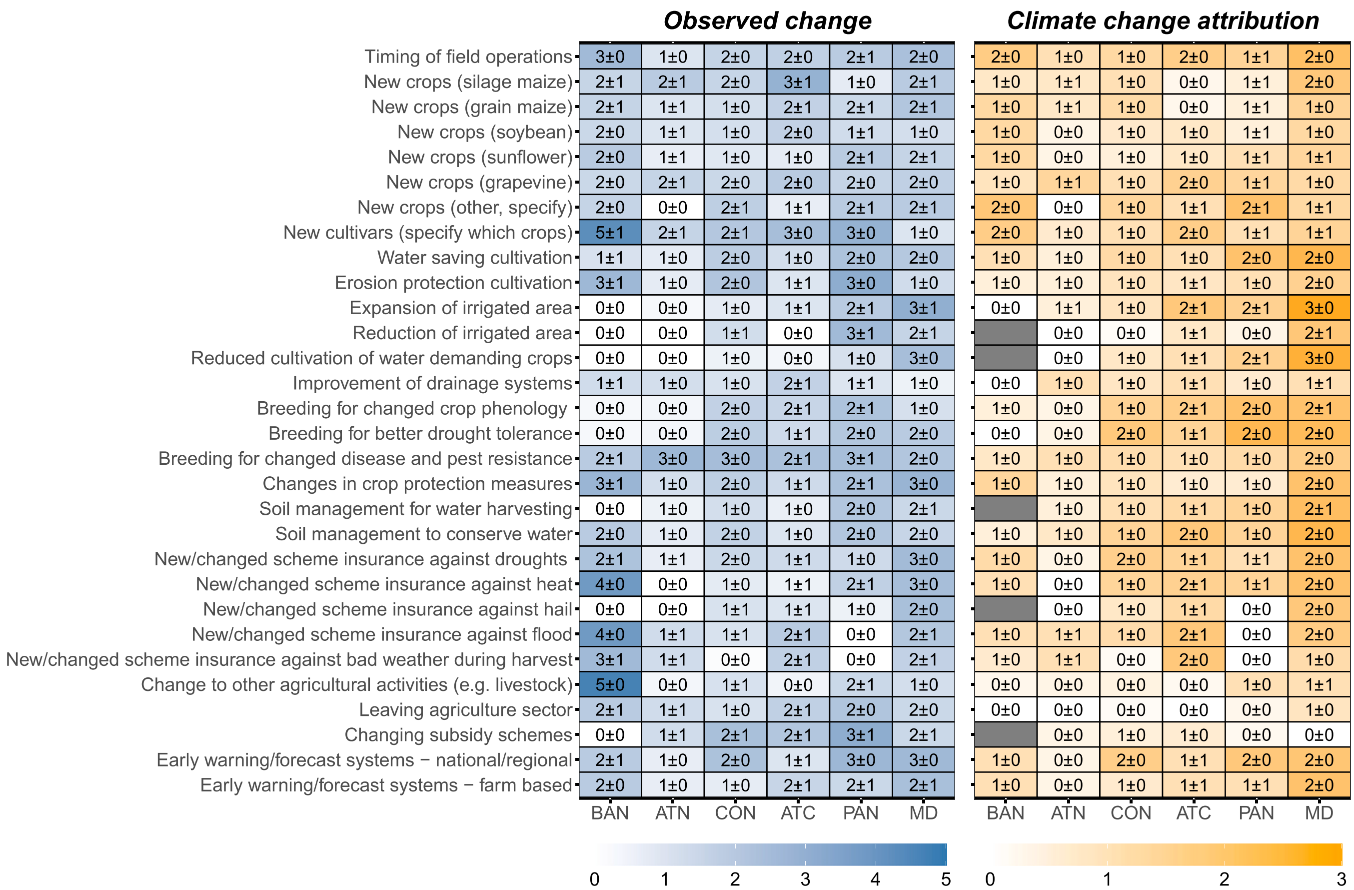

Fig. 3. General observed changes in cropping practices and climate change attributions across European environmental zones. Grey coloured grids indicate areas without applicable information.

implemented for water and organic matter conservation to cope with unprojected changes in rainfall amount and distribution caused by climate change.

3.2.8. *Crop insurance*

Although the high frequency of rainy conditions may meet the crop water requirements in BAN, drought in May is still a problem in some countries, and this is an issue for insurance (Fig. 3). In Finland, a national crop failure compensation system against drought, heat, flood, and bad weather during harvest was ceased in 2016, while a similar system of a combined weather risk insurance for farmers is implemented in Austria. In MD, small to medium changes in scheme insurance were observed against drought, heat, hail, flood, and bad weather during harvest, and climate change have pronounced attribution to this.

3.2.9. *Change of cropping system*

According to the respondents, major changes in agricultural activities happened in BAN, where some areas became less suitable for crop production and a steady increase in the number of animals per farm was reported in Finland (Fig. 3). The opposite trends with livestock systems converting to crop production were observed in some other countries, such as Estonia and Latvia. Changes in agricultural activities are small in other EnZs. In all six EnZs, changes in leaving the agricultural sector and subsidy schemes ranged from no to medium, but there were no climate change attributions of these changes, and they were mostly caused by financial situations and regulations (Bakker et al., 2015).

3.2.10. *Early warning/forecast systems*

Small to medium changes in early warning/forecast systems were found in all the EnZs at national/regional scale, particularly important in PAN and MED (Fig. 3). Meanwhile, changes at the farm scale were smaller.

3.3. *Specific observed adaptations for main crops*

3.3.1. *Wheat*

The use of wheat cultivars with higher temperature requirements from more southern regions and replacing spring wheat with winter wheat were two major adaptations to climate change in BAN due to the warmer conditions (Fig. 4 and Table 3). The introduction of more drought-resistant cultivars is considered important to adapt to climate change in CON, ATC, PAN, and MD. Also, planting more waterlogging-tolerant and heat-resistant cultivars were considered important to adapt to climate change in MD. Minor changes in irrigation, fertilisation, and herbicide use were observed across EnZs, but the contribution from climate change was assumed minor. Traditional diseases (e.g., tan spot, yellow rust, *Fusarium* head blight, *Septoria*, etc.) are commonly found with higher intensities in ATN, ATC, and MD due to climate change, although there may be shifts in dominance of specific diseases, and more frequent fungicide treatments are required as an adaptation.

In BAN, earlier sowing of spring wheat was used as an adaptation to the warmer temperatures (Kaukoranta and Hakala, 2008; Peltonen-Sainio and Jauhiainen, 2014), while later sowing for winter wheat were reported in Lithuania to avoid excessive vegetative growth during the warmer pre-winter period. In addition, significant trends towards earlier harvest were observed under warmer and drier environments in the central and southern European EnZs (CON, ATC, PAN, and MD). Among the cultivations and management strategies, major shifts in the timing of the tillage practices and an increase in cropping areas were assumed effective adaptations for wheat to climate change in

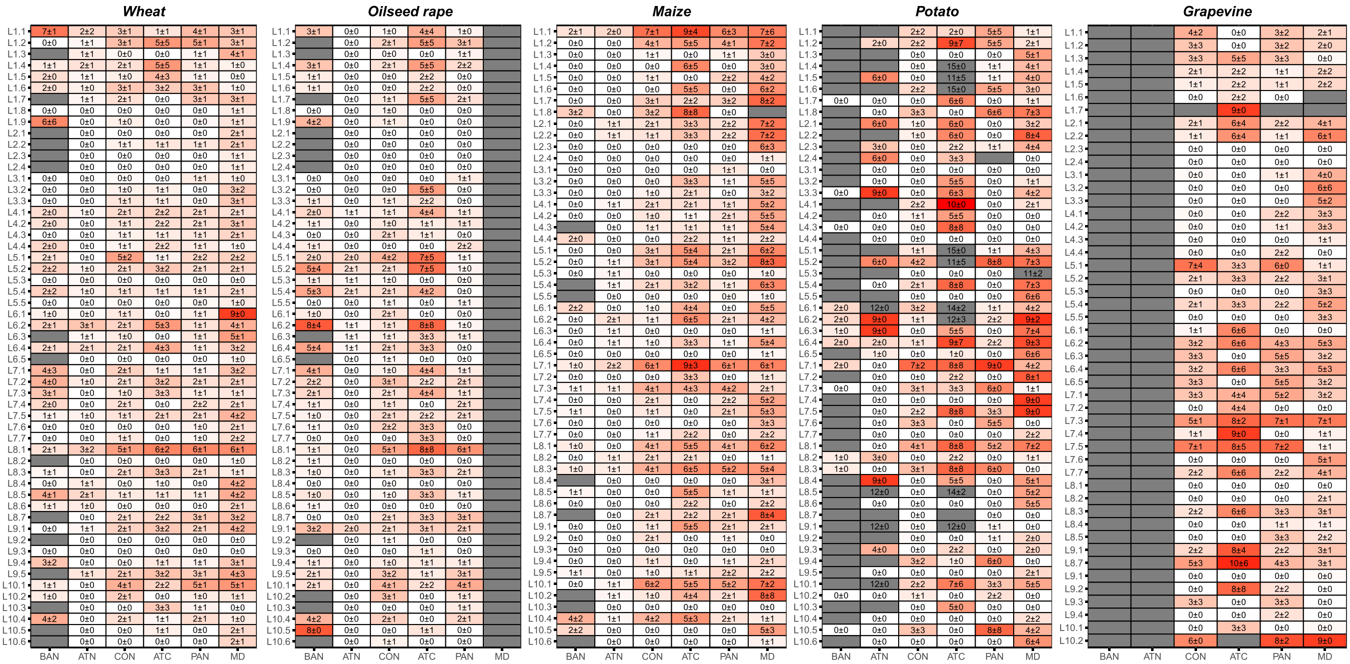

Fig. 4. Average scores of the observed adaptations to climate change (observed changes multiplied by climate change attributions) for wheat, oilseed rape, maize, potato and grapevine across European environmental zones. Grey coloured grids indicate areas without applicable information.

BAN, while this was not an issue in ATN. Furthermore, the shifts in soil management practices are considered as an adaptation to climate change in MD.

3.3.2. *Oilseed rape*

In BAN, replacing early maturing turnip rape with oilseed rape, which has higher temperature requirements and higher yields, was used as an adaptation to the warming climate (Fig. 4 and Table 3). Winter oilseed rape was also selected to adapt to the warming climate, such that the crop is well established before winter, in BAN and ATC. The introduction of more drought-tolerant cultivars was a consistent adaptation for all the three EnZs in central Europe (CON, ATC, and PAN), while more heat-resistant cultivars were reported in ATC to counteract negative effects of heat during flowering and seed filling periods. More frost-resistant winter oilseed rape cultivars were introduced in some countries in BAN and ATC because of the increased frost risk. Further, winter oilseed rape has replaced spring oilseed rape because of higher yield potential due to both climatic and economic reasons in BAN (in regions where it is sufficiently winter hardy).

An increase in the fertilisation rate is suggested in ATC to support higher yields. New pests (e.g., *Ceutorhynchus pleurostigma*, *Plutella xylostella*), higher intensity of traditional pests (e.g., *slugs*, *Phyllotreta*, *Brassicogethes aeneus*, *Ceutorhynchus obstrictus*, *Dasineura brassicae*, *Meligethes aeneus*) and traditional diseases (e.g., *Phoma lingam*, *Leptosphaeria maculans*, *Alternaria*) were reported in BAN and ATC, where more frequent treatments are required. A higher cropping area with oilseed rape has promoted clubroot (*Plasmodiophora brassicae*) in Estonia and the prohibition of chemicals harmful for bees in Lithuania is causing farmers to switch from oilseed rape to other crops or using resistant cultivars.

Similar to wheat, there is clear evidence of earlier sowing of spring oilseed rape as an adaptation in BAN, while earlier harvesting was adopted to avoid storm and hail in CON, ATC and PAN. To offset the negative effects of increasing drought and heat stress as well as the risk of soil erosion, use of minimum tillage is recommended in all the EnZs. Soil water-conserving practices were thought to be effective in CON and PAN.

3.3.3. *Maize*

The use of maize cultivars with higher temperature requirements and the introduction of more drought-resistant cultivars were considered effective adaptations to climate change for maize production in CON, ATC, PAN and MD (Fig. 4 and Table 3). In ATC, the introduction of cultivars with resistance to low temperatures and new diseases was also expected to be adaptations to new problems under climate change, and for MD considerations are given for cultivars with resistance to pests, diseases, and heat. A significant increase in grain maize areas was found in BAN, CON and ATC.

In ATC, CON and MD, more frequent pest and diseases treatments are required with higher intensities of pests (e.g., *Agriotes sordidus*, maize borer, western maize root worm, and spider mites) and diseases (e.g., head smut, *Sphacelotheca reiliana*, *Fusarium*, *Helminthosporium spp*, *Setosphaeria turcica*, *Kabatiella zeae*, and *Puccinia sorghi*) under climate change.

Both earlier sowing and harvest dates were assumed adaptations to climate change in central and southern Europe (CON, ATC, PAN and MD), and wider sowing and harvest windows were observed in the four EnZs, except in MD where a narrower sowing window was reported. Because of wet soils, quicker harvesting is required in ATC, while an increase in post-harvesting drying is required for late cultivars, but a decrease in post-harvest drying is required for early varieties. A decrease in post-harvest drying requirement is reported in MD. As the weather condition have become more suitable for maize in BAN, CON, and ATC, grain maize planting areas have increased in many of these EnZs. However, silage maize planting areas decreased in some countries in BAN. In CON, ATC, PAN, and MD, soil water conservation practices coupled with the introduction of more drought-resistant cultivars were introduced to adapt to the increased drought under climate change. Furthermore, an increase in minimum tillage and intercropping was found in ATC, and intercropping increased in MD.

3.3.4. *Potato*

Cultivar adjustments were thought to be an important adaptation to climate change in ATC and MD. In ATC, this included the introduction of cultivars with more drought and heat resistance, and tolerances to pest and disease (Fig. 4 and Table 3). In PAN and MD, more early potatoes

Table 3
Lists of the adaptation measures presented by the codes in Fig. 4.

Category	Code	Wheat	Oilseed rape	Maize	Potato	Grapevine
Cultivar	L1.1	Use of cultivar with higher temperature requirements	Use of cultivar with higher temperature requirements	Use of cultivar with higher temperature requirements	Use of cultivar with higher temperature requirements	Use of cultivar with higher temperature requirements
	L1.2	Introduction of more drought resistant cultivars	Introduction of more drought resistant cultivars	Introduction of more drought resistant cultivars	Introduction of more drought resistant cultivars	Introduction of more drought resistant cultivars
	L1.3	Introduction of more water stagnation tolerant cultivars	Introduction of more water stagnation tolerant cultivars	Introduction of more water stagnation tolerant cultivars	Introduction of more water stagnation tolerant cultivars	Introduction of more frost damage resistant cultivars
	L1.4	Introduction of more frost damage resistant cultivars	Introduction of more frost damage resistant cultivars	Introduction of more frost damage resistant cultivars	New cultivars with resistance/tolerance to previously not occuring pest	New cultivars with higher tolerance to pest previously not occuring in the area
	L1.5	New cultivars with resistance/tolerance to previously not occuring pest	New cultivars with resistance/tolerance to previously not occuring pest	New cultivars with resistance/tolerance to previously not occuring pest	New cultivars with resistance/tolerance to previously not occuring disease	New cultivars with resistance/tolerance to disease previously not occuring in area
	L1.6	New cultivars with resistance/tolerance to previously not occuring disease	New cultivars with resistance/tolerance to previously not occuring disease	New cultivars with resistance/tolerance to previously not occuring disease	Switch to heat resistant cultivars	Switch to less winter cold tolerant cultivars
	L1.7	Switch to heat resistant cultivars	Switch to heat resistant cultivars	Switch to heat resistant cultivars	Switch to late form (if applicable)	Switch to cultivars with shorter growing period to minimise climate risk
	L1.8	Switch to spring form (if applicable)	Switch to spring form (if applicable)	Switch to grain form (if applicable)	Switch to early form (if applicable)	
	L1.9	Switch to winter form (if applicable)	Switch to winter form (if applicable)			
Irrigation	L2.1	Irrigation newly introduced	Irrigation newly introduced	Irrigation newly introduced	Irrigation newly introduced	Irrigation newly introduced
	L2.2	Irrigation increased (area or amount)	Irrigation increased (area or amount)	Irrigation increased (area or amount)	Irrigation increased (area or amount)	Irrigation increased (area or amount)
	L2.3	Irrigation decreased (area or amount)	Irrigation decreased (area or amount)	Irrigation decreased (area or amount)	Irrigation decreased (area or amount)	Irrigation decreased (area or amount)
	L2.4	Irrigation stopped	Irrigation stopped	Irrigation stopped	Irrigation stopped	Irrigation stopped
Fertilisation	L3.1	Decrease of fertilisation rate	Decrease of fertilisation rate	Decrease of fertilisation rate	Decrease of fertilisation rate	Decrease of fertilisation rate
	L3.2	Increase of fertilisation rate	Increase of fertilisation rate	Increase of fertilisation rate	Increase of fertilisation rate	Increase of fertilisation rate
	L3.3	Different fertilisation schedules	Different fertilisation schedules	Different fertilisation schedules	Different fertilisation schedules	Different fertilisation schedules
Weeds/ Herbicides	L4.1	New previously unknown weed types	New previously unknown weed types	New previously unknown weed types	New previously unknown weed types	New previously unknown weed types
	L4.2	Higher persistance of weeds (compared to the main crop)	Higher persistance of weeds (compared to the main crop)	Higher persistance of weeds (compared to the main crop)	Higher persistance of weeds (compared to the main crop)	Higher persistance of weeds (compared to the main crop)
	L4.3	Increase in herbicide use	Increase in herbicide use	Increase in herbicide use	Increase in herbicide use	Increase in herbicide use
	L4.4	Decrease in the herbicide use	Decrease in the herbicide use	Decrease in the herbicide use	Decrease in the herbicide use	Decrease in the herbicide use
Pests	L5.1	New pests	New pests	New pests	New pests	New pests
	L5.2	Traditional pests with higher intensity	Traditional pests with higher intensity	Traditional pests with higher intensity	Traditional pests with higher intensity	Traditional pests with higher intensity
	L5.3	Traditional pests with lower intensity	Traditional pests with lower intensity	Traditional pests with lower intensity	Traditional pests with lower intensity	Traditional pests with lower intensity
	L5.4	More frequent pest treatments required	More frequent pest treatments required	More frequent pest treatments required	More frequent pest treatments required	More frequent pest treatments required
	L5.5	Less frequent pest treatment required	Less frequent pest treatment required	Less frequent pest treatment required	Less frequent pest treatment required	Less frequent pest treatment required
Diseases	L6.1	New diseases	New diseases	New diseases	New diseases	New diseases
	L6.2	Traditional diseases with higher intensity	Traditional diseases with higher intensity	Traditional diseases with higher intensity	Traditional diseases with higher intensity	Traditional diseases with higher intensity
	L6.3	Traditional diseases with lower intensity	Traditional diseases with lower intensity	Traditional diseases with lower intensity	Traditional diseases with lower intensity	Traditional diseases with lower intensity
	L6.4	More frequent disease treatments required	More frequent disease treatments required	More frequent disease treatments required	More frequent disease treatments required	More frequent disease treatments required
	L6.5	Less frequent disease treatment required	Less frequent disease treatment required	Less frequent disease treatment required	Less frequent disease treatment required	Less frequent disease treatment required
Sowing	L7.1	Earlier sowing dates	Earlier sowing dates	Earlier sowing dates	Earlier planting dates	Earlier pruning dates
	L7.2	Later sowing dates	Later sowing dates	Later sowing dates	Later planting dates	Increase number of pruning operations
	L7.3	More wide-spread sowing window	More wide-spread sowing window	More wide-spread sowing window	More wide-spread planting window	Earlier harvesting dates
	L7.4	More narrow sowing window	More narrow sowing window	More narrow sowing window	More narrow planting window	Later harvesting dates
	L7.5	Quicker sowing required (less suitable days)	Quicker sowing required (less suitable days)	Quicker sowing required (less suitable days)	Quicker planting required (less suitable days)	More wide-spread harvesting window

(*continued on next page*)

Table 3 (*continued*)

Category	Code	Wheat	Oilseed rape	Maize	Potato	Grapevine
	L7.6	Inrease of the seed rate	Inrease of the seed rate	Inrease of the seed rate	Inrease of overall planting density	More narrow harvesting window
	L7.7	Decrease of the seed rate	Decrease of the seed rate	Decrease of the seed rate	Decrease of overall planting density	Quicker harvesting required (less suitable days)
Harvest	L8.1	Earlier harvesting dates	Earlier harvesting dates	Earlier harvesting dates	Earlier harvesting dates	Increase in the tillage operations
	L8.2	Later harvesting dates	Later harvesting dates	Later harvesting dates	Later harvesting dates	Decrease in the tillage operations
	L8.3	More wide-spread harvesting window	More wide-spread harvesting window	More wide-spread harvesting window	More wide-spread harvesting window	Use of mulch/cover crop
	L8.4	More narrow harvesting window	More narrow harvesting window	More narrow harvesting window	More narrow harvesting window	Major time shift in the tillage practices
	L8.5	Quicker harvesting required (less suitable days)	Quicker harvesting required (less suitable days)	Quicker harvesting required (less suitable days)	Quicker harvesting required (less suitable days)	Quicker tillage required (less suitable days)
	L8.6	Increase in post-harvest drying required	Increase in post-harvest drying required	Increase in post-harvest drying required	Increase in post-harvest drying required	
	L8.7	Decrease in post-harvest drying required	Decrease in post-harvest drying required	Decrease in post-harvest drying required	Decrease in post-harvest drying required	
Cultivation	L9.1	Increase in the minimum tillage	Increase in the minimum tillage	Increase in the minimum tillage	Increase in the minimum tillage	Soil water conserving plans introduced
	L9.2	Increase in the "convential" tillage (ploughing)	Increase in the "convential" tillage (ploughing)	Increase in the "convential" tillage (ploughing)	Increase in the "convential" tillage (ploughing)	Inter-row cropping use increased
	L9.3	Increase in the deep tillage	Increase in the deep tillage	Increase in the deep tillage	Increase in the deep tillage	Inter-row cropping use decreased
	L9.4	Major time shift in the tillage practices	Major time shift in the tillage practices	Major time shift in the tillage practices	Major time shift in the tillage practices	Increase in the crop area
	L9.5	Quicker tillage required (less suitable days)	Quicker tillage required (less suitable days)	Quicker tillage required (less suitable days)	Quicker tillage required (less suitable days)	Decrease in the crop area
	L9.6					Abandonment of growing the crop
Management strategies	L10.1	Soil water conserving plans introduced	Soil water conserving plans introduced	Soil water conserving plans introduced	Soil water conserving plans introduced	Is there a need to add more sugar
	L10.2	Intercropping use increased	Intercropping use increased	Intercropping use increased	Intercropping use increased	Is there a need to add less sugar
	L10.3	Intercropping use decreased	Intercropping use decreased	Intercropping use decreased	Intercropping use decreased	
	L10.4	Increase in the crop area	Increase in the crop area	Increase in the crop area	Increase in the crop area	
	L10.5	Decrease in the crop area	Decrease in the crop area	Decrease in the crop area	Decrease in the crop area	
	L10.6	Abandonment of growing the crop	Abandonment of growing the crop	Abandonment of growing the crop	Abandonment of growing the crop	

were planted to escape from late blight because of rainy autumns and the vulnerability to late occurring pests and diseases, and frost stress, as well as for market reasons.

Due to greater variability in weather conditions with increased frequency of heatwaves and droughts, more farmers consider to increase irrigation, including newly introduced irrigation in ATN, ATC, and MD, for example, drip irrigation, which is projected to be a cost-efficient adaptation measure to maintain high tuber quality (Schaap et al., 2013). However, the risk of salinization may decrease irrigation in some areas. Split fertiliser application was assumed to reduce the risk of nitrate leaching in ATN, ATC, and MD under climate change.

New weed types and higher persistence of weeds (e.g., *Cyperus*), new and traditional pests (e.g., *Agriotes sordidus*, *Meloidogyne artiellia*, *Meloidogyne chitwoodi*, and *aphids*), and new and traditional diseases (e.g., *Alternaria*, *Erwinia*, and *Phytophthora infestans*) had increased in BAN, ATC and CON due to the higher temperature and humidity, and resulted in increased pesticide use. Use of *Phytophthora infestans* resistant cultivars is seen as a strategy of adaptation in BAN, although climate change has promoted the sexual reproduction of the pathogen, implying that the strategy might not be sustainable (Runno-Paurson et al., 2019d).

Earlier planting and harvest dates are considered adaptations in CON, ATC and PAN; later planting dates were observed due to climate change in MD, while more narrow planting and harvest windows and quicker planting and harvest are required. In ATC and ATN, larger farm sizes have resulted in a wider planting and harvesting window, but at the same time narrower harvest windows have been made possible due to self-propelled 4-row potato harvesters. The introduction of new extra-early varieties and crop protection are expected to be more important in the case of potato. The greater occurrence of weed or disease was picked up by most respondents. The productivity of potato is further reduced due to the spread of insects during droughts. This situation is even worse for many non-irrigated potato areas, when summer rainfall is insufficient to fully meet crop water requirements, which consequently leads to a substantial reduction in the cultivation area. Most studies report that early- and mid-potato varieties can only be grown successfully under irrigated conditions (e.g., Iliev, 2016), which is consistent with the perception of farmers. Whereas tuber formation of late varieties is consistent with the highest summer temperatures and the lack of water in the soil and air. Cultivation and management strategies play a greater role in adaptation to climate change in ATN and ATC than for other EnZs.

3.3.5. Grapevine

For grapevine, responses were only received from the central (CON, ATC and PAN) and southern (MD) European EnZs (Fig. 4 and Table 3). In CON and PAN, the use of cultivars with higher temperature requirements, more drought and frost damage tolerance are reported as adaptations in the northern cropping areas. In other regions, cultivars were switched to ones with shorter growing periods to minimise the climate risk, for example for Chardonnay in ATC.

To offset the greater water demands under climate change, irrigation increased in ATC, PAN and MD. Adjusted fertilisation was found in MD to better regulate grapevine vegetative growth and to optimise the vigour-yield ratio.

Different pests and diseases showed different tendencies among the four EnZs, which adversely affect grapevine production and cause considerable economic damages. More frequent treatments are required, while treatments for some specific pests (e.g., *Lobesia botrana*) and diseases (e.g., *downy mildew*) may be less.

Earlier pruning and harvest dates are expected to be an adaptation to climate change in all four EnZs. However, increased numbers of pruning operations and later harvest dates were also observed for some cultivars in ATC. A wider harvesting window was considered an adaptation in CON, ATC and PAN, while a narrower harvesting window was reported in MD. For erosion control and soil water conservation, soil water-conserving plans and increased inter-row cropping are used in all the four EnZs under climate change. In CON and PAN, the higher temperatures could shift grape cultivation towards higher latitudes and altitudes, where this may increase sugar content, and consequently boost wine quality significantly. On the other hand, this may reduce acidity. In Austria (CON) in recent years specific registered white wine types did not reach their required minimum acidity. However, in south-eastern Europe, extreme weather conditions with prolonged dry periods and high temperatures, as well as heavy rain events can severely influence viticulture productivity and wine quality. Moreover, quality wine areas might be at risk due to increased water needs, decreased yields and changes in grape composition (aromatic compounds, i.e. higher contents of alcohols, volatile fatty acids, esters, aldehydes, and terpenes) that may reduce wine quality.

3.4. Planned adaptations for European cropping systems

The questionnaire asked about 25 general planned adaptation responses and 13 specific adaptations for the five crops that were thought to be applicable throughout most of the EnZs and would be picked up by respondents. Among the listed adaptations to climate change, changed timing and adopted practices of field operations, fertilisation regime, and crop protection were only suggested or considered by some experts in all the six EnZs, except changed field operation practices in CON and changed crop protection in BAN being recommended in general (Fig. 5).

Cultivars adapted to warmer and drier climate and other climate-proof cultivars have been suggested in MD. Such adaptations are also being considered or recommended in general for other European EnZs. In addition, crop yield may also benefit from using optimal cycle duration and sowing date. For instance, maize yields over Europe may increase despite climate change, when the genetic variation in flowering time is appropriately harnessed (Parent et al., 2018).

Soil erosion control, soil fertility protection and monitoring of drought, pests, and diseases are expected to be relevant adaptation options across Europe. Expansion and improvement of irrigation systems, landscape changes (e.g., hedgerows, buffer strips), and revised environmental regulations and subsidy schemes are part of adaptation planning in MD, while they are being considered or only suggested in the other parts of Europe. Soil and water conservation techniques reduce water stress in ATC, while the costs of irrigation are not justified (de Frutos Cachorro et al., 2018). Crop rotations for better water and nutrient use are being introduced as part of adaptation planning in BAN, ATN and MD. The switched focus of the production (e.g. high-quality products) and microclimate modification is being considered or suggested in all of the six EnZs. In contrast, leaving the agriculture sector was not thought of as an effective adaptation to climate change in any part of Europe.

For the five specific crops, different scores were given about the listed adaptations to climate change in the six EnZs (Fig. 6). As for the general adaptations, changed timing and practices of field operations, use of seasonal weather forecasts, and introduction of irrigation have

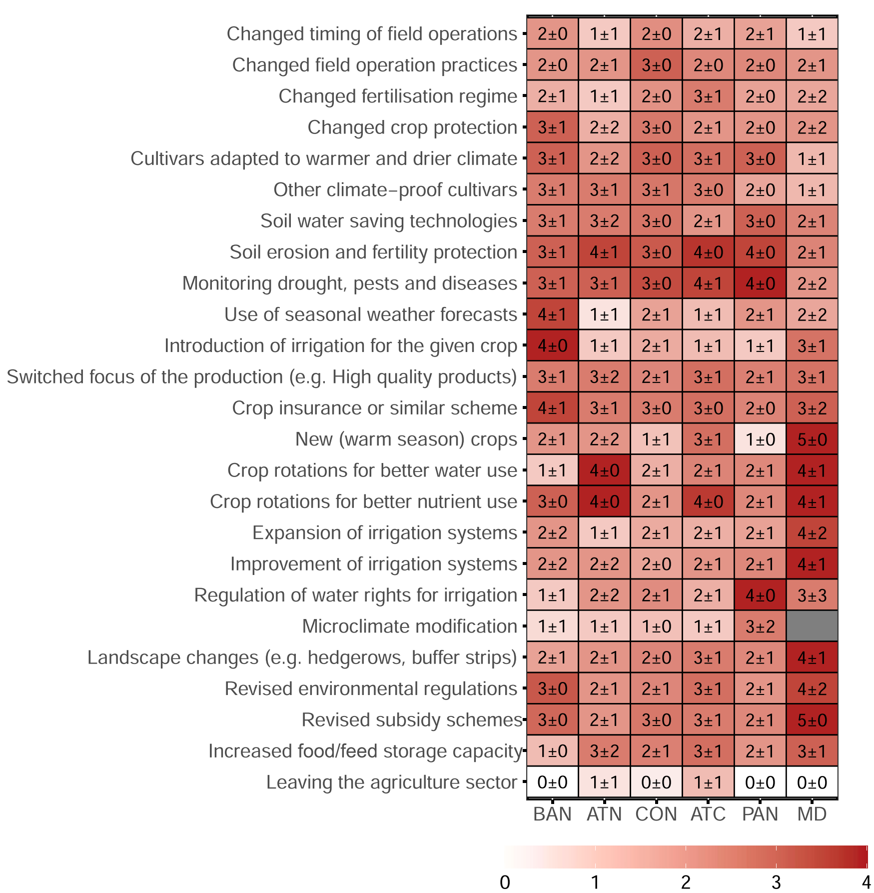

Fig. 5. Average scores of the generally planned adaptations to climate change across European environmental zones. Grey coloured grids indicate areas without applicable information.

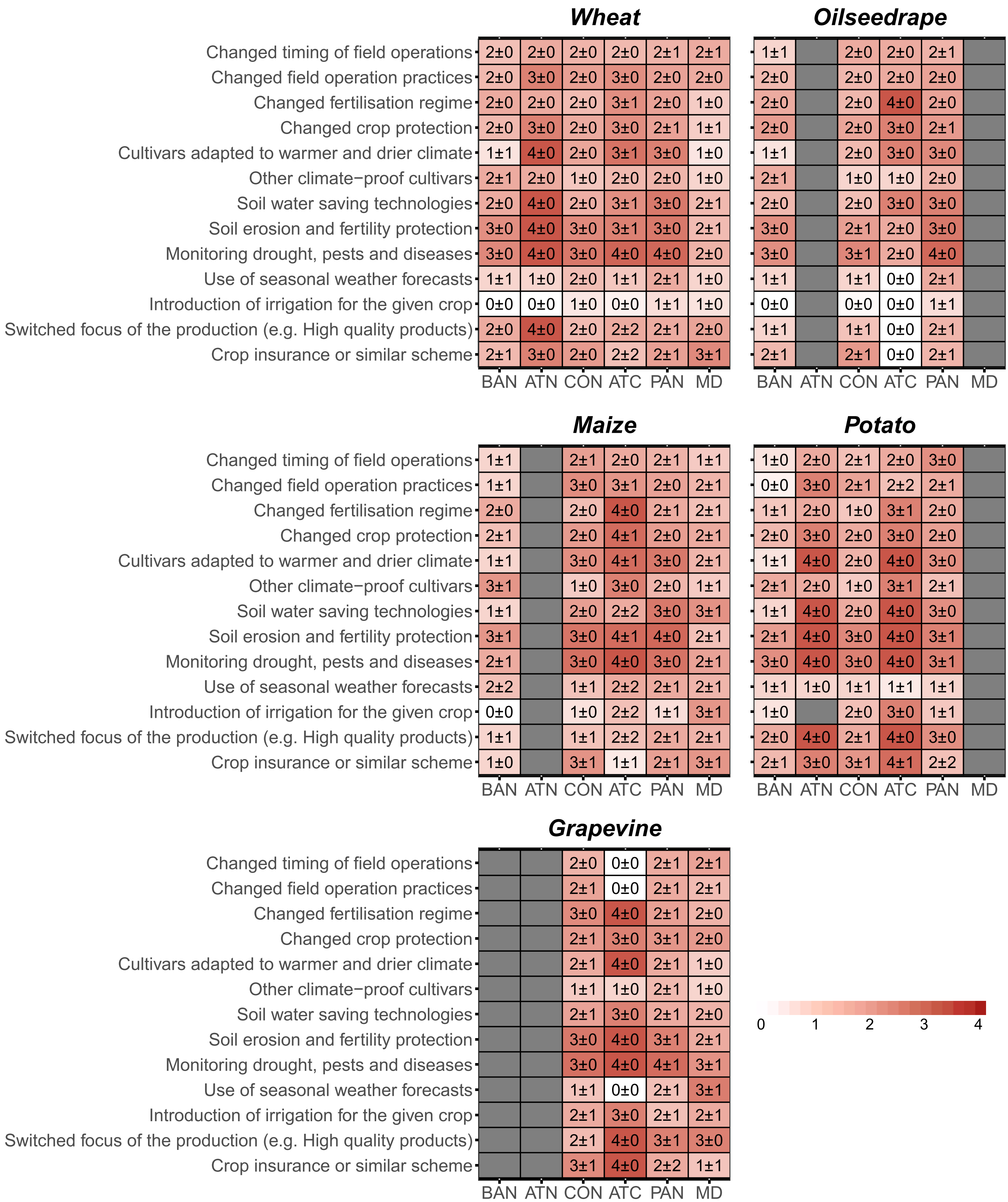

Fig. 6. Average scores of the planned adaptations to climate change for the five crops across European environmental zones. Grey coloured grids indicate areas without applicable information.

only been suggested or considered by some experts for all the five crops in all six EnZs, except changed field operation practices being recommended in general for wheat and potato.

Soil erosion prevention, soil fertility protection and monitoring of drought, pests and diseases are being recommended or introduced as part of adaptation planning for all crops in all the EnZs. Additionally, cultivars adapted to a warmer and drier climate, soil water-saving technologies, and switched production focus are being introduced as part of adaptation planning for wheat and potato in ATN. In ATC, CON and PAN, cultivars adapted to warmer and drier climate and soil water-saving technologies are also being planned to adapt to climate change for all the five crops, while switched production focus and crop insurance or similar scheme are only planned for potato and grapevine in ATC. In MD, crop insurance or similar scheme are being recommended in general for wheat and maize; for instance, in Spain, where the insurance system has a major role for agricultural activity, the State Entity for Agricultural Insurance is conducting an exercise to adapt the system to climate change. In MD, the use of seasonal weather forecasts and switched production focus are being recommended in general for potato and grapevine.

Across all environmental zones there are concerns for the need of changes in both agricultural subsidy schemes and in environmental regulations, although there is no or little concern for the option to abandon farming (Fig. 5). These concerns were particularly high for BAN and MD, where changes in climatic conditions have particularly large consequences for agriculture. In MD, ATN and ATC there are stated needs to increase the storage capacity of feed and food in order to better buffer variation in crop production as affected by increased weather extremes.

4. Discussion

4.1. Changes in cropping systems

In northern Europe (BAN and ATN), crop production is limited by cool temperatures (Holmer, 2008), and planting areas of wheat and oilseed rape have increased consistently over time, possibly linked to the warming climate as well as economy of the cultivation. The area of maize and grape is very limited (less than 0.1×10^6 ha) in BAN and ATN, because the periods offering suitable temperatures for these warm-season crops are currently too short in cold temperature zones (Olesen et al., 2011). Potato production is highly sensitive to water stress (Razzaghi et al., 2017), and a higher frequency of droughts reported in some countries of CON may have contributed to the decreasing trend in potato cropping area. Besides, the stagnation of potato cropping area due to new strains of diseases such as *Phytophthora* as well as market conditions, and much of potato growing areas have been replaced by oilseed rape and cereals. In southern Europe (MD), the decreasing trends of all the considered crops (except for oilseed rape) is most likely due to higher temperature and lower rainfall, causing severe water deficits and reduction in the irrigation water availability (Camps and Ramos, 2012; Olesen et al., 2011). Pullens et al. (2019) has recently shown that oilseed rape in southern Europe may become increasingly vulnerable to climatic stresses.

Changes in cropping systems are mostly caused by changes in socioeconomic, market conditions, and emerging diseases such as the explosive spread of African swine fever in the Baltic countries and Poland in 2014, and further spread to multiple other EU countries since then. However, the cropping system is not keeping pace with climate change, as is the case for maize systems in MD (Potop, 2011), where the warming and drought that occur between growing and final seed usage result in unintentionally shorter crop duration (earlier sowing and earlier harvests). A shift to cereals in systems traditionally used with root crops (e.g., potato) is estimated as an effective way to maintain farm economic results and improve soil organic matter balance under future climate change and extreme events (Mandryk et al., 2017; de Frutos Cachorro et al., 2018).

4.2. Adaptations of crops and cultivars

The changes in the timing of field operations were mostly attributed to an earlier onset of the growing season, especially in the cooler zone (BAN) (Peltonen-Sainio and Jauhiainen, 2014; Uleberg et al., 2014; Wiréhn, 2018). To adapt to the warmer conditions, earlier sowing of spring crops and later sowing for winter crops have been conducted across all the five crops (Juknys et al., 2017). However, the timing of field operations is also determined by other coinciding changes (e.g., socioeconomic factors, soil water content). For example, increased farm size increases workload per farm in the spring, which has emphasised the need for taking advantage of early sowing, which again has been supported by new farm technologies (Kaukoranta and Hakala, 2008). Also, the local pedo-climatic and socioeconomic conditions play a role for the timing of field operations such as documented for Moldova in central Europe (CON and PAN) (Boincean, 2014).

Adaptation to climate change through crop changes had positive impacts on the farmer's individual utility (de Frutos Cachorro et al., 2018). For specific regions in Northern Europe, the enhanced cultivation of silage maize was primarily attributed to warmer temperatures increasing the competitiveness of the crop (Elsgaard et al., 2012). In Germany, the cultivation of Merlot, Cabernet Sauvignon, and Syrah, which are adapted to higher temperatures has increased during the latest decade (UBA, 2019). Besides, cropping areas of other crops have increased, such as buckwheat, triticale, camelina, winter oilseed and turnip rape, caraway, and faba bean in BAN (Peltonen-Sainio et al., 2016a; Peltonen-Sainio and Jauhiainen, 2020), horticultural crops, legumes on dryland in MD (Iliev, 2016), soybean, grain maize and durum wheat in the south of Germany (CON and ATN) (UBA, 2019).

In general, farmers continuously adopt their cultivar portfolio and purchase higher yielding cultivar seeds that at the same time produce good quality and remain robust against lodging, pests, and diseases (Kahiluoto, 2019; Peltonen-Sainio et al., 2016b; Potopová et al., 2019; Rijk et al., 2013). For all the five crops, cultivars of southern origin have shown good performances under the experienced higher temperatures (Mäkinen et al., 2018). In BAN, significant changes in new cultivars were reported, of which later maturing spring wheat cultivars substitute earlier maturing wheat cultivars, and later maturing oilseed rape cultivars substitute earlier maturing turnip rape cultivars (Palosuo et al., 2015; Peltonen-Sainio et al., 2009, 2016a, 2017; Peltonen-Sainio and Jauhiainen, 2014). In contrast, UBA (2019) reports that the significant earlier flowering of oilseed rape in Germany is partly related to earlier flowering cultivars, which were selected by farmers due to advantages in pest and disease management, especially against rape pollen beetle (*Meligethes aeneus*). In Estonia, farmers also choose earlier cultivars of wheat and oilseed rape to reduce risks during wet harvest conditions. In Belgium, crop diversification helps reduce crop losses due to extreme weather events (de Frutos Cachorro et al., 2018; Gobin, 2010, 2012). In central and southern Europe, cultivars with heat and drought tolerance were selected by farmers in many countries (Gobin, 2012; Potopová et al., 2016; Spinoni et al., 2018; Trnka et al., 2019). For some specific cultivars, the suitable cropping areas have moved northward. For example, cereal cultivars from France had been planted in Germany. The higher temperatures could also shift grape cultivation towards higher latitudes and altitudes, where this may increase sugar content, and consequently boost wine quality significantly (Cramer et al., 2018; Potopová et al., 2020). Furthermore, as adaptation potential of cultivars to extremes vary with regions, a major future breeding challenge will be to evaluate the potential of combining such cultivar traits with other traits required under different growing conditions, for example, long-day conditions at higher latitudes when the intensity and frequency of extremes rapidly increase (Mäkinen et al., 2018). There is also a need to consider the diversity of traits among genotypes, since no single genotype may be suitable under all conditions with the projected increase in climatic variability (Kahiluoto et al., 2019).

4.3. Adaptations of soil and water management

The time shift of tillage practices could lead to less accumulated effective radiation and thus potentially to lower yields (Trnka et al., 2015). An increase in the minimum tillage and soil water conservation practices (e.g., mulching, cover crops) are important in the central and southern European EnZs, while in northern Europe catch crops are needed to retain nutrients in warming autumns with higher precipitation (Peltonen-Sainio et al., 2018).

Although there is no reported change in soil management for enhanced water harvesting for the high precipitation regions in BAN (Iglesias and Garrote, 2015; Trnka et al., 2011), soil management to conserve water (e.g., no-till and residue retention) has become popular, but it is mostly attributed to improved farm management. In some rain-fed winter-sown fields in MD, no-tillage was implemented for water and organic matter conservation to cope with unpredicted changes in rainfall amount and distribution caused by climate change.

Because of the high annual precipitation in the northern Europe (Trnka et al., 2011), there was no change in irrigated areas and cultivations. A large farmer survey in Finland revealed that implementation of irrigation was the least important adaptation measure for the farmers (Peltonen-Sainio et al., 2020). However, newly introduced irrigation was assumed to play an important role in adapting to the water deficit caused by the warming climate, with an increase in irrigated area, but decreased amount of irrigation in central and southern Europe (Fraga et al., 2012, 2016, 2017; Klein et al., 2013; Monaco et al., 2014; Wiréhn, 2018). In particular in MD, supplementary irrigation of cereals is thought to overcome some of the detrimental effect of the complex interactions imposed by climate and CO_2 perturbations (Ruiz-Ramos et al., 2018), and in viticulture the current irrigation schemes will no longer be sufficient to maintain the quality of grapes in the near future (Resco et al., 2016). The transition of selected rainfed and currently fully irrigated areas to supplementary irrigation could be a feasible strategy, as expanding the area of full irrigation is highly questionable since the current water policy in Europe limits additional irrigation due to resource scarcity (Iglesias and Garrote, 2015). Furthermore, irrigation is constrained due to a high degree of salinization and water-saving restrictions and/or the need for pumping in some countries. For example, Aragüés et al. (2011) reported that soil salinity is related to physical soil characteristics and irrigation management in four Mediterranean irrigation districts. This may make irrigation too expensive, and the cost of irrigation often exceeds its potential benefits (Potopová et al., 2016; de Frutos Cachoro et al., 2018; Potopová et al., 2019).

Improvement of drainage systems may be needed in some areas in response to increased precipitation and flooding risks (Peltonen-Sainio et al., 2015), as also largely agreed by farmers (Peltonen-Sainio et al., 2020). In addition, improved drainage (e.g., increased capacity of the sub-surface tile system and investment in the proper reconstructions of main drainage systems) will also be needed to cope with increased precipitation and heavy rains and decrease the drought sensitivity of crop production in Northern Europe (Wiréhn, 2018). Meanwhile, increased precipitation and runoff will increase the nutrient runoff risk from the agricultural soils (Huttunen et al., 2015). The vulnerability to soil erosion is particularly high in arable row crops such as potato, maize and sugar beet (Vanwindekens et al., 2018), and here additional measures may need to be taken to protect the soil.

4.4. Adaptations through decision support and insurance

Changes in crop protection are expected to be one of the prominent adaptation measures to climate change (Olesen et al., 2011; Yin et al., 2016), especially in the Nordic region (Wiréhn, 2018). Winter wheat is an example of a crop that often needs intensive spraying against pests and diseases, and the warmer and wetter conditions for winter wheat in Northern Europe could enhance the risk of diseases (e.g., mildew), pest and weed overwintering, thus increasing the need for pesticide application (Henriksen et al., 2013; Wiréhn, 2018). This has already happened in potato production (Lehsten et al., 2017). The enhanced use of decision support systems for supporting crop protection has in many cases reduced the use of pesticides to control the specific diseases and pests by better targeting their use (Hakala et al., 2011).

Crop insurance is an effective way to reduce the farmers' economic loss under extreme climatic conditions (Gobin, 2018), and the highest importance is reported for zones where the most negative impacts of adverse weather are expected (Olesen et al., 2011; Yin et al., 2016). Increasing climatic and market risks, as well as policy reforms (e.g., changes in the direct payments system of the EU CAP), recently increased the demand for new insurance schemes that cover more than single risks in agriculture (Diaz-Caneja et al., 2009), increasing, in turn, the demand for re-insurance products. Besides, EU mutual funds can be used for compensating farmers for losses suffered in EU countries (Meuwissen et al., 2013).

Early warning/forecast systems are expected to be effective to overcome some stresses due to changed climate conditions and would be beneficial for both farmers and insurance companies (Gobin, 2018). Some software systems were developed and used by farmers. They may get the warning/forecast information on extreme weather (e.g., drought, flood, and heat), disease outbreaks, and pest invasions (Pertot et al., 2017) by e-mail, text messages, or internet-based platforms, and be used to plan agronomic operations (e.g., irrigation, fertilisation, crop protection).

4.5. Limitations of the study

This is to our knowledge the first study that attempts to cover the whole suite of factors affecting crop production under altered climate and possible adaptations across Europe and a range of crops. Such a comprehensive assessment cannot rely on rigorous experimental or modelling studies only, but will by its nature need to rely on the insight and experience of crop production experts. Therefore, we designed a questionnaire survey to capture these insights and experiences from experts across Europe.

Due to the limitations of the number of survey respondents, the scores may not exactly represent the varying conditions in each EnZ and the difference among the crops. However, while the results are based on the expertise and knowledge of experts, we do achieve a full coverage of national and regional climate change and adaptations across all the European environmental zones for a range of crops, which is, in our opinion, a real asset of this manuscript. The consistency in evaluation and feedback of the original results could also reduce the uncertainty. This study provides a picture of the extent of climate adaptation measures in agricultural cropping systems. The thorough understanding of the foreseen adaptations in the different zones will be helpful for supporting decision making at both farm and policy levels.

5. Conclusions

Based on expert surveys, we mapped the observed and planned adaptations and quantified their attributions to climate change for key crops (wheat, oilseed rape, maize, potato, and grapevine) in six EnZs across Europe. The results show that there are large regional variations in observed and planned adaptations to climate change in general and for each of the five crops in Europe. In northern Europe, changed timing of field operations and introductions of new crops and cultivars were observed and are also expected as the main adaptations to the prolonged growing season and declined low-temperature constraints under climate change. Meanwhile, farmers in central and southern Europe are adapting to climate change, mainly by changing water and soil management, and introducing new cultivars with better drought tolerance to cope with increasingly erratic rainfall. In general, observed adaptations are more often attributed to climate change in the Mediterranean compared to other EnZs. Due to the increased climate-related risks and extremes, more advanced integrated crop protection measures, use of crop insurance, and early warning/forecasting systems may provide ways to reduce economic losses and become prominent adaptation measures across Europe, but the risks and extremes may be different for different crops in different EnZs.

In the future, changed timing and practices of field operation, fertilisation regimes, crop protection, soil water conservation practices and climate-proof cultivars are expected to be prominent adaptation measures across Europe. Expansion and improvement of irrigation systems, landscape changes, and revised environmental regulations and subsidy schemes are being introduced as part of adaptation planning in southern Europe due to the projected warmer and drier climate.

CRediT authorship contribution statement

JEO and MT designed and performed the research. MB, JE, RF, ZG, AG, AH, KCK, JK, ZK, EL, PN, CN, ÜN, TP, PP, VP, MRR, PR, VR, MvI worked as the national contact points to select experts and collect the responses. JZ analyzed the data and wrote the paper. All the authors contribute to the paper writing and revisions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2022.126516.

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