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Review

Impacts and adaptation of European crop production systems to climate change

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ABSTRACT

The studies on anthropogenic climate change performed in the last decade over Europe show consistent projections of increases in temperature and different patterns of precipitation with widespread increases in northern Europe and decreases over parts of southern and eastern Europe. In many countries and in recent years there is a tendency towards cereal grain yield stagnation and increased yield variability. Some of these trends may have been influenced by the recent climatic changes over Europe.

A set of qualitative and quantitative questionnaires on perceived risks and foreseen impacts of climate and climate change on agriculture in Europe was distributed to agro-climatic and agronomy experts in 26 countries. Europe was divided into 13 Environmental Zones (EZ). In total, we had 50 individual responses for specific EZ. The questionnaires provided both country and EZ specific information on the: (1) main vulnerabilities of crops and cropping systems under present climate; (2) estimates of climate change impacts on the production of nine selected crops; (3) possible adaptation options as well as (4) adaptation observed so far. In addition we focused on the overall awareness and presence of warning and decision support systems with relevance for adaptation to climate change.

The results show that farmers across Europe are currently adapting to climate change, in particular in terms of changing timing of cultivation and selecting other crop species and cultivars. The responses in the questionnaires show a surprisingly high proportion of negative expectations concerning the impacts of climate change on crops and crop production throughout Europe, even in the cool temperate northern European countries.

The expected impacts, both positive and negative, are just as large in northern Europe as in the Mediterranean countries, and this is largely linked with the possibilities for effective adaptation to maintain current yields. The most negative effects were found for the continental climate in the Pannonian zone, which includes Hungary, Serbia, Bulgaria and Romania. This region will suffer from increased incidents of heat waves and droughts without possibilities for effectively shifting crop cultivation to other parts of the years. A wide range of adaptation options exists in most European regions to mitigate many of the negative impacts of climate change on crop production in Europe. However, considering all effects of climate change and possibilties for adaptation, impacts are still mostly negative in wide regions across Europe.

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Contents

1. Introduction

Europe is one of the world's largest and most productive suppliers of food and fibre. In 2008 it accounted for 19% of global meat production and 20% of global cereal production. About 80% of the European meat and 63% of the cereals is produced in the EU27 countries. The productivity of European agriculture is generally high, in particular in western Europe, and average cereal yields in the EU countries are more than 60% higher than the world average.

Intensive farming systems in western and central Europe generally have a low sensitivity to climate change, because a given change in temperature or rainfall have modest impact (Chloupek et al., 2004), and because the farmers have resources to adapt and compensate by changing management (Reidsma et al., 2010). However, there may be considerable difference in adaptive capacity between cropping systems and farms depending on their specialisation (Reidsma et al., 2007). Intensive systems in cool climates may therefore respond favourably to a modest climatic warming (Olesen and Bindi, 2002). On the other hand some of the farming systems currently located in hot and dry areas are expected to be most severely affected by climate change (Reilly and Schimmelpfennig, 1999; Darwin and Kennedy, 2000). There is a large variation across the European continent in climatic conditions, soils, land use, infrastructure, political and economic conditions (Bouma et al., 1998). These differences are expected also to greatly influence the responsiveness to climatic change (Olesen and Bindi, 2002; Trnka et al., in press).

The scale of the ongoing changes in European crop production is wide-ranging and cannot be fully covered by national studies that are usually not based on comparable methodologies. Without a thorough understanding of the regional differences it is difficult to foresee necessary changes in the agricultural policies at EU or national scales. The objective of the present study was therefore to gather and analyse standardised information on vulnerabilities, impacts and adaptation to climate change for selected crops for European environmental zones. The study relied on the expertise of European scientists and researchers, who were approached independently with a series of standardised questions.

2. Observed and projected changes in Europe

2.1. Observed climate change

Most of Europe has experienced increases in surface air temperature during 1901–2005, which amounts to 0.9 °C in annual mean temperature over the entire continent (Kjellström, 2004; Alcamo et al., 2007). However, the recent period shows a trend considerably higher than the mean trend (+0.4 °C/decade for the period 1977–2001, Jones and Moberg, 2003). For the past 25 years, trends are higher in central and north-eastern Europe and in mountainous regions, while the lowest temperature trends are found in the Mediterranean region (Klein Tank, 2004). Temperatures are increasing more in winter than in summer (EEA, 2004; Jones and Moberg, 2003). An increase in temperature variability has been observed, primarily due to increase in warm extremes (Klein Tank and Können, 2003).

There are indications of changes in the rainfall pattern as indicated by the frequency of drought events during spring and early summer. There has been an increased occurrence of droughts in large parts of western and eastern Europe, with particularly large increases in the Mediterranean region (Trenberth et al., 2007). Mean annual precipitation is increasing in most of Atlantic and northern Europe and decreasing along the Mediterranean (Klein Tank et al., 2002). An increase in mean precipitation per wet day has been observed in most parts of the continent, even in areas getting drier (Frich et al., 2002; Klein Tank et al., 2002). The increase in rainfall intensity has led to incidents of severe summertime flooding in Europe (Christensen and Christensen, 2003). The severity of the floods was probably enhanced by human management of the river systems, e.g. diking and construction of reservoirs (Helms et al., 2002), and possibly by changes in agricultural land use in the river basins (van der Ploeg and Schweigert, 2001).

Other studies show that the number of stations with statistically significant trends towards drier conditions (in terms of available soil moisture), prevail in central Europe over those where either no trend at all or a tendency toward wetter conditions were noted (Szinell et al., 1998; Trnka et al., 2009). These shifts in intensity and frequency of drought in the region were shown to be largely driven by changes in near surface temperatures (van der Schrier et al., 2007) and associated with changes in circulation patterns (Trnka et al., 2009). The droughts might be combined with extreme heat waves as was the case in 2003, when large parts of Europe were exposed to summer temperature rises of 3–5 °C. This heat wave was associated with an annual precipitation deficit up to 300 mm, and the drought was a major contributor to the estimated reduction of 30% over Europe in gross primary production of terrestrial ecosystems (Ciais et al., 2005). The heat wave also led to widespread reductions in farm income (Fink et al., 2004).

2.2. Projections of climate change

Most of the recent global climate model (GCM) experiment results, used in Europe for analysing effects on agricultural systems, are based on coupled ocean–atmosphere models (AO-GCM). The main modelling uncertainties stem from the contrasting behaviour of different climate models in their simulation of global and regional climate change (Olesen et al., 2007). These uncertainties are largely a function of the relatively coarse resolution of the models and the different schemes employed to represent important processes in the atmosphere, biosphere and ocean. There has recently been an increased effort in downscaling the coarse GCM results using regional climate models (RCM) with spatial resolutions of 50 km or less (Christensen and Christensen, 2007; Christensen et al., 2007). This has led to improved quality in projections of regional climate changes in Europe.

The expected warming is greatest over eastern Europe during winter and over western and southern Europe in June–July–August (Giorgi et al., 2004). The projected increase in summer temperatures is very large in the south-western parts of Europe (exceeding 6 °C in parts of France and the Iberian Peninsula) by the end of the 21st century under the A2 emission scenario, which describes a heterogeneous world with high population growth, slow economic development and slow technological change. Generally for all emission scenarios and climate models, the mean annual precipitation increases in northern Europe and decreases in the South. But the change in precipitation varies substantially from season to season and across regions (Christensen and Christensen, 2007). There is a projected increase in winter precipitation in northern and central Europe, whereas there is a substantial decrease in summer precipitation in southern and central Europe, and to a lesser extent in northern Europe.

There is relatively little difference in projected climate changes between emission scenarios up to about 2050. Recent climate change projections for Europe based on GCMs and RCMs for the A1B scenario for 2050 show annual temperature increases relative to 1961–90 of 1.5–3 °C and 2–3 °C for northern and southern Europe, respectively (van der Linden and Mitchell, 2009). The corresponding projected changes in annual rainfall are 5–10% increase in northern Europe and 0–10% decrease in southern Europe. The A1B emission scenario describes a world of rapid economic growth, a global population that peaks in mid-century and more efficient technologies based on a balanced energy mix.

It is very likely that the frequency of drought spells and their severity will increase at least in some regions of Europe (the southern and central parts in particular), and recent projections of climate change impacts support this hypothesis (e.g. Hayes et al., 2005; Calanca, 2007). Recent results also indicate that variability in temperature and rainfall may increase considerably over large parts of central Europe (Christensen and Christensen, 2003; Schär et al., 2004). Indeed heat waves and droughts similar to the 2003 situation may become the norm in central and southern Europe by the end of the 21st century (Beniston and Diaz, 2004).

2.3. Observed changes in cropping patterns

The highest yields of both cereal and tuber crops are obtained in western Europe and the lowest yields in southern and eastern Europe. By far the largest cropping areas are found in eastern Europe, in particular in the Russian Federation and Ukraine. The cropping areas of eastern Europe are larger than the total of all other regions for wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), potato (*Solanum tuberosum* L.), and sugar beet (*Beta vulgaris* L.).

The development in national grain yields of wheat in the period 1961–2009 is shown in Fig. 1 for selected countries in northern, central and southern Europe. Yields in northern Europe are limited by cool temperatures (Holmer, 2008), whereas yields in southern Europe are limited by high temperatures and low rainfall (Reidsma and Ewert, 2008). Yields increased considerably during the period 1970–1990 due to improved technologies in all countries with the highest absolute increases in western and central Europe. The yield increases have levelled off considerably during the past 10–20 years. There seems to be a small yield increase during the past 10–20 years in Finland, whereas yields in Greece have been declining. Both effects may be climate related with increasing temperatures being beneficial in Finland, but negative in Greece. The wheat yields in Germany and Greece seem to indicate an increased yield variability, which most likely is also related to climate. However, compared to its neighbouring countries, Switzerland and Austria, the stagnation of the yield trend in Germany starts about 10 years later due to a continued increase of yields in the new federal states of the former GDR during the 1990s. Stagnating wheat yields in France have been attributed to lower yields under the rising temperatures (Brisson et al., 2010), but changes in management may also have played a role in some countries (Finger, 2010). There are also clear indications that increasing temperatures are causing grain yield reductions globally (Lobell and Field, 2007).

Grain yields in maize (*Zea mays* L.) have been increasing over the period 1961–2009 in both central and southern Europe (Fig. 2). The yield increases seem to be continuing in Belgium and Germany, even in recent years, where wheat yield increases have been levelling off. This has also resulted in a steadily increasing grain maize area in these countries and a northward shift of the grain maize cultivation in Germany. The yield of grain maize in France and Italy has not increased in recent years. This is most likely due to warmer cli-

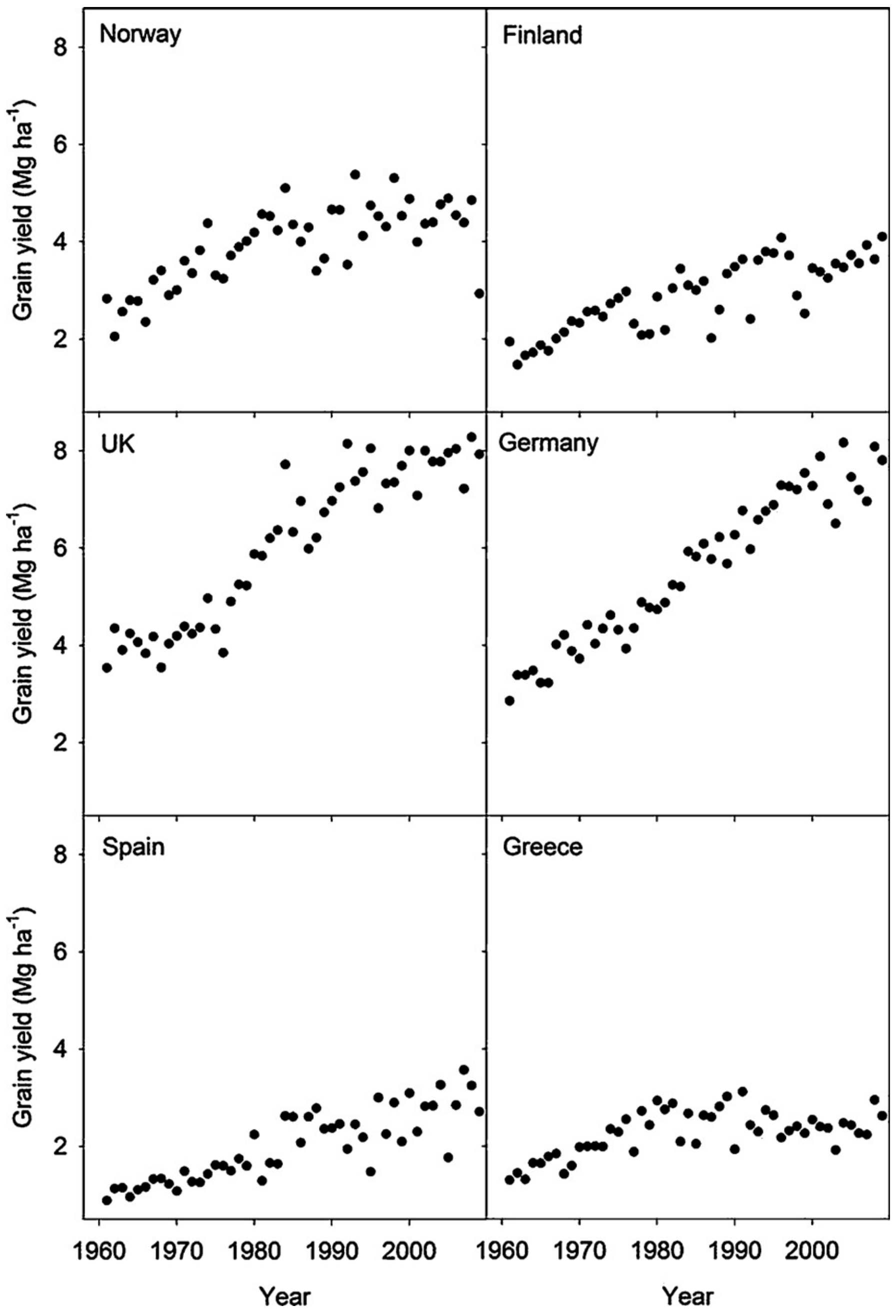

Fig. 1. National grain yield of wheat in northern, central and southern European countries for the period 1961–2009 (FAOSTAT database).

mate and a higher frequency of droughts, which reduces the water available for irrigation, and since maize is predominantly an irrigated crop in these countries, this has impacted on both maize yields and the area cropped with maize.

3. Material and methods

To gather information on perceived risks and foreseen impacts of climate change on agriculture in Europe we designed a set of qualitative and quantitative questionnaires that were distributed to agrometeorological and agronomy experts in 26 countries that are mostly members of the COST 734 project. These experts did not include farmers or agricultural advisers, but mostly covered agricultural researchers knowledgeable on national and regional climate and climate change effects on crops. The questionnaires provided rather detailed information on: (1) main vulnerabilities of crops and cropping systems under present climate; (2) estimates of climate change impacts on the production of nine selected crops; (3) possible adaptation options; (4) adaptation observed so far and (5) on the overall awareness and presence of warning and decision support systems.

It was assumed that within climatically homogenous zones both the present crop production limitations as well as the climate change impacts on crop production will show a high degree of consistency, given the same trends of climate change. As a consequence there should be marked differences between individual zones. As the climate conditions do not follow national boundaries, it was decided to relate responses to the questionnaires to particular climate zones rather than to countries. To do so the environmental zones (Fig. 3) recently defined by Metzger et al. (2005) and Jongman et al. (2006) were used and each respondent was

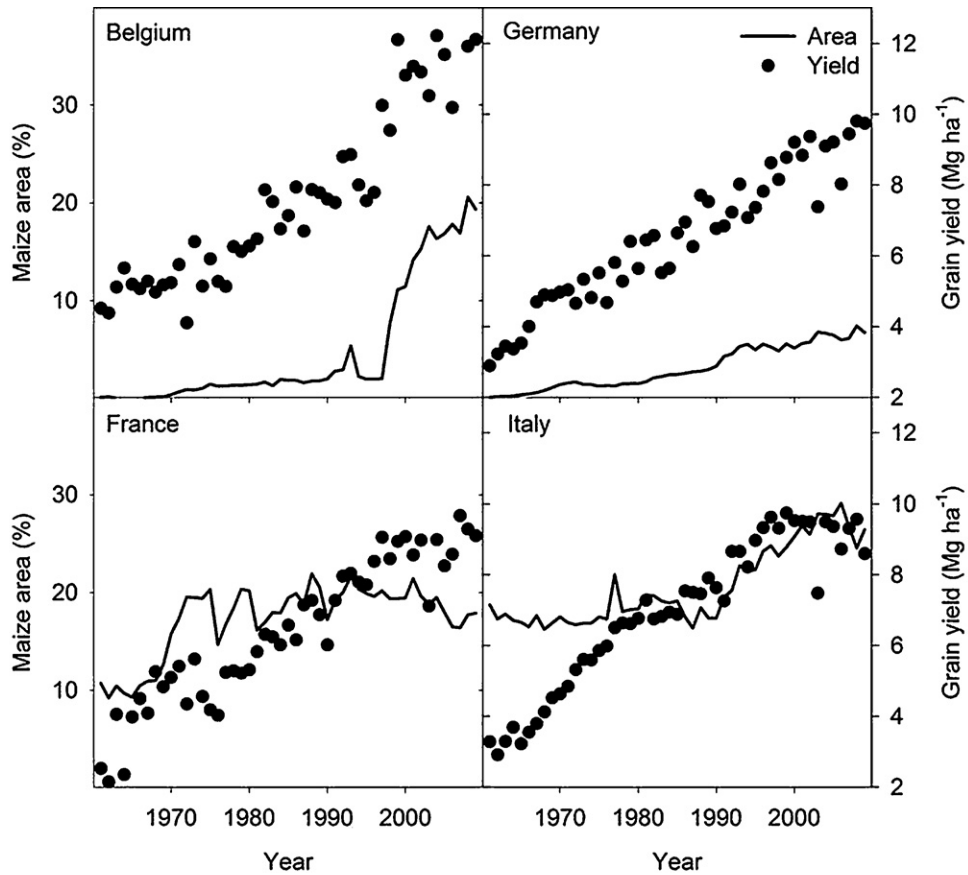

Fig. 2. National grain yield and area of grain maize in four countries in northern and southern Europe for the period 1961–2009 (FAOSTAT database).

asked to provide information specific to each environmental zone that could be found in his/her country. It is believed that the use of the environmental zones enable a much better interpretation due to the more sensitive and meaningful grouping of individual responses compared to a grouping based on national boundaries as performed by Olesen and Bindi (2002).

The questionnaires included specific questions within the following overall groups:

1 Current limitations of individual crops to climatic conditions for the individual crops (scale in Table 1).
2 Projected climate change impacts by 2050 for individual crops (scale in Table 1).
3 Projected use of adaptation options by 2050 for the individual crops (scale in Table 1).
4 Observed use of adaptation options that can be attributed to climate change for the individual crops (scale in Table 1).

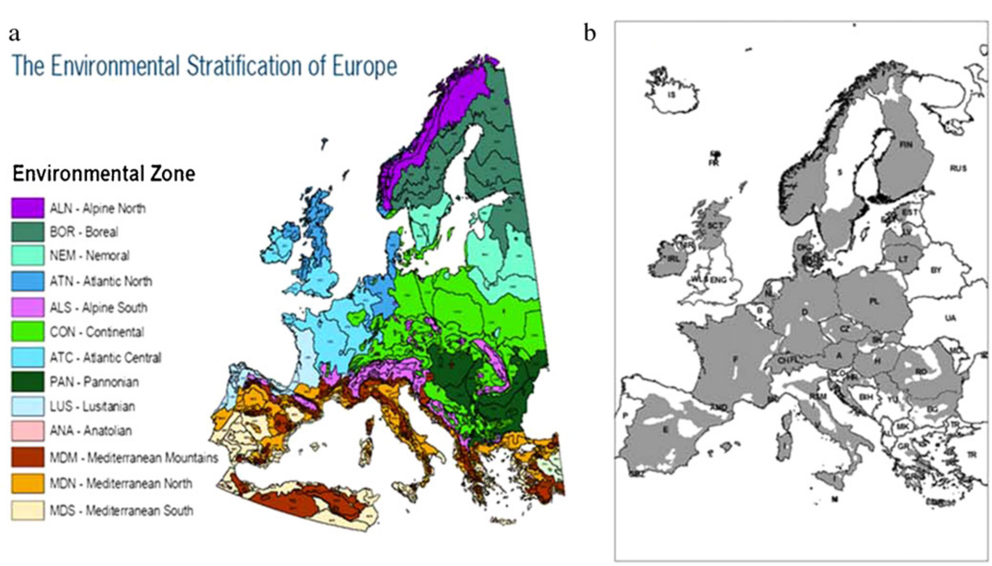

Fig. 3. a) Environmental zones in Europe according to (Metzger et al., 2005; Jongman et al., 2006) and b) the area covered by the questionnaires in grey.

Table 1
Scales used in the survey for scoring present limitations of crops to climatic conditions, projected climate change impacts by 2050 and use of adaptation options.

Score	Explanation
Present limitation to climatic conditions	
NA	Not applicable (e.g. crop not grown)
NI	No information
0	No problem
1	Minor problem, occurs rarely, no detectable effects on regional production
2	Small problem, occurs sometimes, small and rare effects on regional production
3	Moderate problem, occurs occasionally, small effects on regional production
4	Major problem, occurs frequently, moderate effects on regional production
5	Large problem, occurs almost every year, major effects on regional production
Projected climate change impacts by 2050	
NA	Not applicable (e.g. crop not grown)
NI	No information
−2	Large decrease
−1	Small decrease
0	No change or no effect even if there is a change in the parameter
1	Small increase
2	Large increase
Adaptation options	
NA	Not applicable (e.g. crop not grown)
NI	No information
0	None
1	Minor
2	Moderate
3	Large

5 Different types of warning and decision support systems for the individual crops that may be relevant under climate change.
6 Adaptation strategies, awareness and dissemination based on a few categories for responses for individual issues (Fig. 8).

The question groups 1–3 were answered specifically for nine selected crops (if applicable): winter wheat, spring barley, grain maize, winter oil seed rape, sugar beet, potatoes, grassland, apple orchards and grapevine (*Vitis vinifera* L.). Here we present results from the five crops with the highest response rate: winter wheat, spring barley, grain maize, grassland and grapevine. Rigid scales were used for each of the question groups 1–4 to allow responses to be compared across environmental zones.

Answering most of the questions involved a degree of a subjective assessment with a scoring that was based on the experts' own evaluations and/or national studies or recent research results. However, a guideline and a set of definitions of terms were provided with the questionnaire in order to unify ratings. This guideline described the projected climate changes by 2050 and how the scales for rating the responses should be applied. The questionnaires were distributed in November 2007 and were collected during February and March 2008. We received responses from 26 countries with 50 individual responses in total. These included all relevant European environmental zones, although the number of responses varied among zones (Table 2), but in overall the majority of EU and associated countries were covered by the answers (Fig. 3b). The only zone completely missing from the survey was the Anatolian zone (ANA) that can be found only in Turkey, which was not included in the study. Although the number of responses varied among zones (Table 2), all of them were covered, and all zones with significant crop production were covered by at least four respondents. It should, however, be noted that the zones with only one or two responses (ALN, BOR and LUS) may be subject to higher uncertainties.

The original results were analysed and the consistency within each environmental zone and with the results of the similar zones was evaluated. When needed the respondents were contacted again to verify their responses (e.g. when any inconsistency occurred between responses within one environmental zone). In the final step the overall results were processed and distributed to the respondents for additional comments.

4. Results

4.1. Present climatic limitations and vulnerabilities

The results of the questionnaire survey indicate that there are considerable differences between individual environmental zones as well as between crops examined in our study with respect to current climatic limitations and vulnerabilities (Fig. 4). Some of the crops could not be evaluated in all zones as grain maize and grapevine are not grown in ALN and BOR and winter wheat is not present in ALN. The length of the growing season limits crop growth considerably in BOR and ALN and also in ATN in case of grapevine. The growing season duration is also a limiting factor for grassland and grapevine production in MDM. On the other hand it is only in LUS, MDN and MDS that temperature does not limit growing season duration for the most temperature demanding crops (grain maize and grapevine).

Damage caused by late frost in spring (or early frost during fall) are seen as a limiting factor particularly in case of grain maize and grapevine in all cooler zones, where these crops are grown (NEM, ATN and CON). In case of grapevine the late frosts seem to be a limiting factor in a number of seasons in PAN, and in case of ALN frost risk for spring barley production is reported in some seasons.

Table 2
Number of responses received within European environmental zones.

Zone	Number of responses per zone	Number of countries/regions
ALN – Alpine North	1	1
BOR – Boreal	2	2
NEM – Nemoral	4	4
ATN – Atlantic North	6	5
ALS – Alpine South	4	4
CON – Continental	10	9
ATC – Atlantic Central	4	4
PAN – Pannonian	4	4
LUS – Lusitanian	1	1
ANA – Anatolian	0	0
MDM – Mediterranean Mountains	4	4
MDN – Mediterranenan North	5	4
MDS – Mediterranean South	5	4
Total	50	46

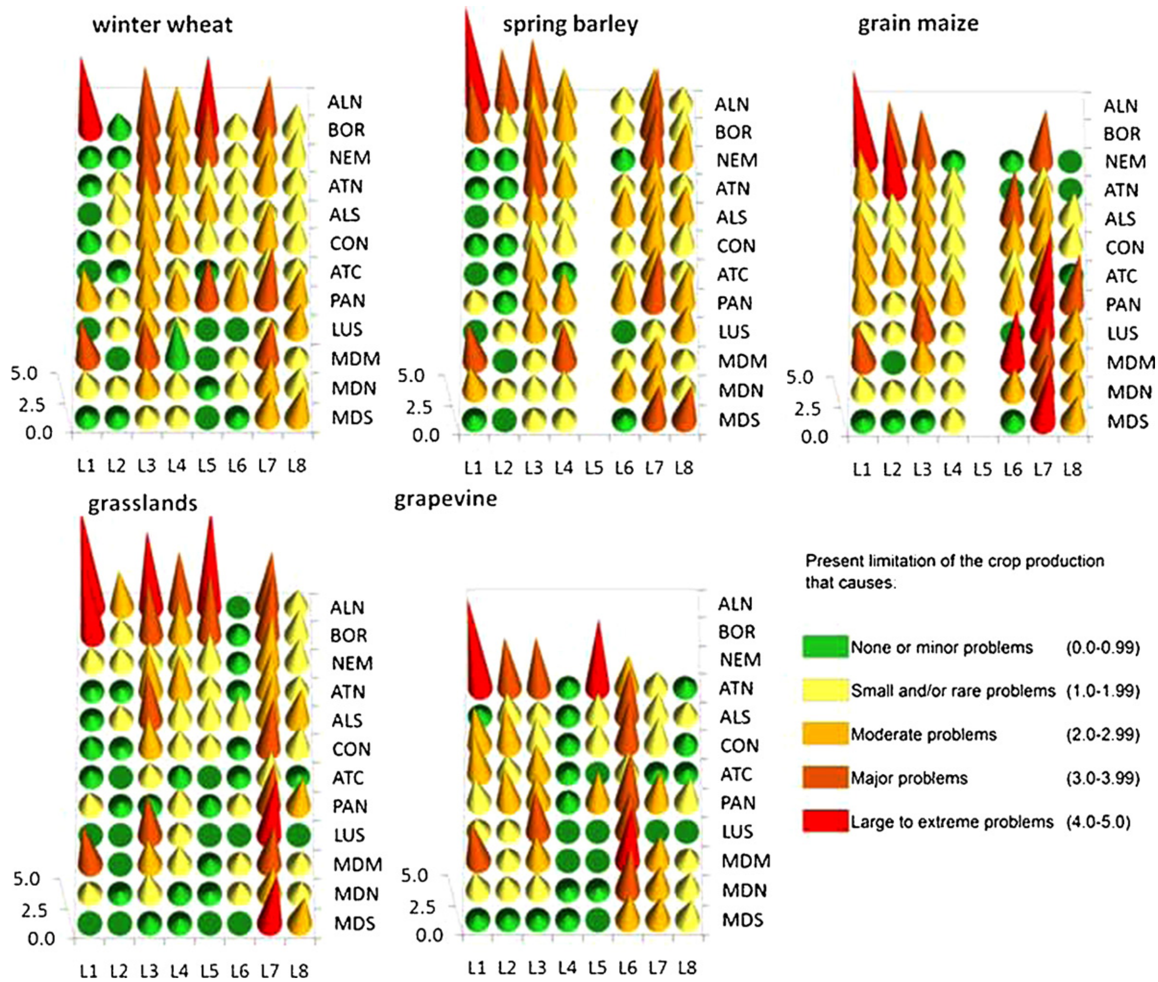

Fig. 4. Present limitation of crop production by climate factors for five selected crops over the individual European environmental zones. Legend: L1 length of the growing season; L2 occurrence of late/early frosts; L3 rain during sowing/harvesting; L4 occurrence of floods; L5 crop damage during winter; L6 crop damage by hail; L7 occurrence of drought; L8 heat stress.

High frequency of rainy conditions complicates sowing and harvest across most of the north-western zones with the highest impact being reported from ALN and BOR. Also in BOR, ATN and ALS rainfall during key field operations seem to be important especially in case of harvesting cereals and hay. On the other hand rainfall is not perceived as a limiting factor for harvest or sowing in MDN and MDS, where conditions are much drier.

Flooding and stagnant surface water in agricultural fields is considered a persistent problem in ALN, BOR, ATN and MDM, especially in case of grasslands, winter wheat and spring barley. Flooding and especially water stagnation was also reported for PAN, especially in the case of cereals. On the other hand respondents did not consider water stagnation or floods as a limitation in ATC, LUS, MDN and MDS. Grapevine seems to be the least affected crop by these phenomena due to terrain (frequently on slopes), soil conditions (often on light and permeable soils) and environmental zones (mostly warmer and drier), where it is grown.

Overwintering and damage to crops during winter is considered a major problem in ALN in case of grasslands and in BOR for grasslands and winter wheat production. Local to regional scale damage was reported also from NEM, ATN, ALS, CON and PAN in case of winter wheat, whilst the effect on grassland is considered to be only marginal in these areas. The damage caused by snow cover and overall winter conditions (including severe frosts) are also threats to grapevine production in ATN and to a lesser extent in ALS, CON and PAN.

Hail damage seems to be a minor problem that occurs rarely and has no detectable effect on regional production in case of wheat, barley and grassland production across most zones. However, it is considered as quite prominent even for all crops in PAN. Lower risk reported for small grain cereals and grassland is most likely given by their relatively high resistance to the damage compared to grain maize and especially grapevine. In case of these two crops the hail damage is seen as a moderate problem in case of ALS, CON, PAN, LUS and MDM.

One of the most interesting findings in our survey has been the prominence of drought as a limiting factor. Whilst drought rarely scores as a severely limiting factor it seems to be of concern across all zones and all crops with exception of grapevine. In case of grapevine the damage is considered to only rarely affect production at regional level. However, it is surprising that grassland or winter wheat production seems to be quite substantially limited not only within warm and dry zones (i.e. MDN or MDS) but also in the mountains (MDM and ALS) as well as in the cool and relatively wet zones in the north (ALN, BOR or NEM). In Finland drought interferes with grass crop establishment and also regrowth after the first cut in the season. For cereals and seed crops drought may be particularly critical at flowering and seed setting, but winter cereals are far better able to escape from drought due to a deep root system compared to spring cereals that are extremely vulnerable. When the total ranking of the individual limiting factors is done across the zones and crops drought appears to be the single most significantly limiting factor.

The pattern of perceived limitations caused by heat stress is much more erratic than for droughts with reported effects mainly for wheat, barley and maize in PAN and partly in the MDS. However, it should be noted that even under present climatic conditions most of the respondents considered this factor to be important even in zones that are not normally viewed as being threatened by this weather phenomena (BOR, NEM or ALS). This indicates that respondents may have been confounding heat stress and droughts, since unusually hot periods often coincide with prolonged dry periods.

4.2. Climate change impacts

4.2.1. Winter wheat

The impacts of climate change on winter wheat are thought to be negative across most of the zones (Fig. 5a). Whilst higher temperatures are expected to enable use of late maturing cultivars in BOR, NEM and ATN thus extending the growth duration, it will also mean shortening of growth in remaining zones with the ATC, LUS, MDM and MDN being most affected. However, the damage during winter and risk of frost damage are expected to be lower in most of the zones with the exception of ALS. Improved conditions for sowing and harvest are expected in NEM, ALS and LUS, and only in MDM zone is notable worsening of the conditions expected.

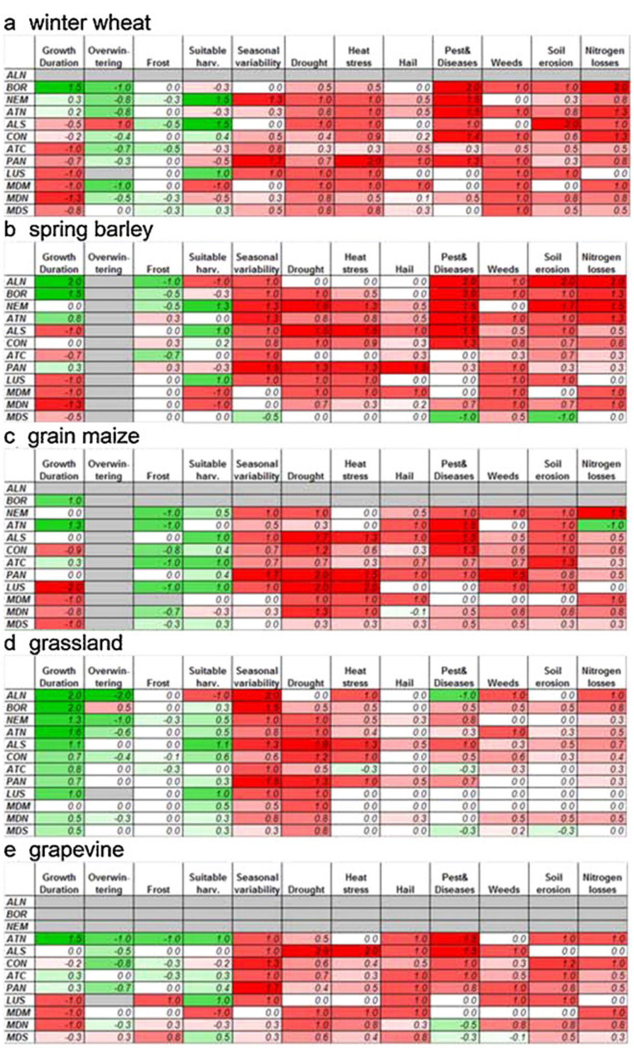

Fig. 5. Expected average scores for impacts of climate change on a range crop production limiting factors for five selected crops: a) winter wheat; b) spring barley; c) grain maize; d) grassland; e) grapevine. The scale used for scoring is presented in Table 1 and colour-coding reflects positive effect (green) or negative effect (red). The grey colour represents area without present crop production.

The changes in the seasonal climate variability are considered to have neutral or negative effect on winter wheat production with NEM and PAN being the most vulnerable. Not surprisingly risk of drought and heat stress is thought to increase in all zones. However, this increase is according to the used scale considered to be small with the exception of heat stress risk in PAN area, where a large increase is expected. The largest threat for the northern and central European zones (BOR, NEM, ATN, ALS, CON and PAN) is thought to be higher risk from plant pathogens and pests, whilst in the southern zones this problem is considered to be only marginal. Higher intensity of weed occurrence or introduction of new weed species has been picked up by most respondents with the exception of NEM and ALS. Risk from soil erosion and nitrate leaching is perceived as much higher in the zones, where increased precipitation is expected (BOR, ATN or ALS), but also mentioned as a threat in the Mediterranean region (MDS and MDN).

4.2.2. Spring barley

As for winter wheat the change in the evaluated parameters is expected to influence spring barley production mostly negatively (Fig. 5b). Higher temperatures are expected to prolong growth duration in the northern range of spring barley growing area (ALN, BOR and ATN), while a negative influence is expected further south, especially in ALS, LUS, MDM and MDN. The frost risk is thought to decrease or remain the same in most of the zones. Improved conditions for harvest are expected in NEM, ALS and LUS, whereas for ALN, MDM and MDN a notable worsening of the harvest conditions is expected.

The impact of changes in the seasonal variability is in general perceived as negative with the exception of Mediterranean area (MDM, MDN and MDS). The respondents expected the largest changes for PAN, NEM and ATN zones. Drought is perceived as a very prominent risk in most of the zones, and spring barley production is thought to be more at risk compared to winter wheat. Damage caused by heat stress is also expected to rise in most of the zones, but with the cooler and continental zones thought to be more vulnerable compared to the MDN or MDS. As was the case for wheat, changes in hail risk do not show any significant pattern with the exception of pronounced risk increase in PAN. On the other hand the expected damage caused by the phytopathogens and pests is significantly greater than in the case of winter wheat. Similar to wheat the negative impacts are thought to dominate in ALN, BOR, NEM, ATN, ALS, CON and ATC, but in the remaining part of Europe no change or even improvements are expected. Higher occurrence of weeds or introduction of new weed species was picked up by most respondents with the exception of NEM. Similar to wheat soil erosion and nitrate leaching are expected to increase under climate change with the exception of MDS.

4.2.3. Grain maize

The estimates of climate change on grain maize production indicate that this C_4 crop species is expected to perform much better than the annual C_3 cereal crops (Fig. 5a–c). Higher temperatures are expected to positively influence length of growing season in BOR and ATN, but to shorten growth duration in CON, LUS, MDM and MDS. Across all zones the decrease of late frost risk is expected as well as increase in the number of suitable days for harvest (although in many cases only small effects). While the impact of drought and heat stress in the colder zones (e.g. NEM, ATN or CON) are thought to be smaller compared to wheat or barley, grain maize seems to be more vulnerable to drought and heat stress in PAN, LUS or MDS as compared with the present conditions. Despite the fact that climate change is expected to lead to increased hail damage, pest and disease risk, increased of weed pressure, higher soil erosion and nitrate leaching, the intensity of these changes are in most zones smaller than those of small grain cereals.

4.2.4. Grassland

Out of our sample of five crops, grassland was perceived by the respondents to be least affected by climate change. Growth duration is expected to increase in all environmental zones, especially in ALN, BOR, NEM, ATN and ALS. Damage during winter and those caused by frosts is expected to decrease and the number of days suitable for harvest is thought to increase (but mostly slightly) in all zones except ALN. Only marginal negative impact is expected from hail occurrence, heat stress, soil erosion, nitrogen leaching and weed occurrence with a notable exception of ALN, where some of these parameters are changing to the worse (Fig. 5d). However, drought and changes of seasonal climate variability is expected to cause negative impact across all zones with quite significant effects in most zones. Interestingly the magnitude of changes (both positive and negative) is thought to be highest in the northernmost zones (ALN, BOR and NEM) with only subtle changes expected for grassland production along the Mediterranean (LUS, MDM, MDN and MDS).

4.2.5. Grapevine

The changed climatic conditions are expected to lead to decrease in winter and frost damage in the cooler ones of the wine-producing zones (ATN, CON or ATC), whereas increased frost risk is expected in the warmest areas (MDS and LUS) (Fig. 5e). Number of days suitable for harvest also increases slightly in most of the zones with a decrease being reported only in MDM zone. The length of the growing season is expected to decrease in LUS, MDM, MDN and slightly in CON and MDS. On the other hand increased temperatures will lead to an increased period of growth in ATN. Despite the fact that changes in all remaining parameters are expected to be negative across most zones, the changes are not expected to be large. Significant increase of drought and heat stress was estimated by our respondents only for ALS and partly for MDN, where irrigation is commonly practiced for this crop. Grapevine production is thought to suffer from increased hail damage across the zones, and higher risk of diseases and pest occurrence is expected especially in ATN and ALS. The soil erosion and nitrate leaching is expected to rise; however, not significantly, probably with the exception of CON, where pronounced increase of soil erosion is expected.

4.3. Observed adaptation responses

The questionnaire asked about 10 specific adaptation responses and about five “new” crop species that were thought to be applicable throughout most of the environmental zones and would be picked up by respondents. Minor to moderate changes in the cultivation timing had been observed in all environmental zones during the recent decade(s). The most significant changes seem to be happening in the cooler zones (BOR, CON, ATC and PAN) compared to the Mediterranean (MDN and MDS). The change of cultivation includes not only changes in tillage practices, but mainly shifts in sowing dates (e.g. earlier sowing of spring crops).

Introduction of new crops to the crop rotation was reported with increasing area of silage and grain maize being the most notable changes. In case of silage and grain maize, ATN and CON show the largest changes. The area of grain maize has increased in the PAN zone. BOR, CON and PAN zones show higher interest in growing of sunflower as a response to changing climate conditions and this goes in hand with introduction of soybeans to these zones. The respondents for NEM, ATN, CON, PAN, MDN and MDS noted increased grapevine production. Whilst in the cooler zones the main driver seems to be more favourable climatic conditions enabling introduction of this crop, in the southern zones the main reason seems to be a higher tolerance of grapevine to drought compared with the arable crops. Especially in the warmest zones (LUS, MDN and MDS), respondents noted a tendency of farmers to reduce crops that are unsuitable under the changing climatic conditions.

Despite the tendency to new cropping schemes, farmers seem to be maintaining the present portfolio of crops. This is documented by a reported tendency to introduce new and more suitable cultivars of presently grown crops across all zones. This is even more evident from a reported increase of interest in the cultivars that are able to cope better with drought and other weather extremes. As the drought has been spotted as one of the most pervasive crop growth limitations, there has been a wide spread effort to promote techniques that preserve soil water, especially in the most drought prone regions (PAN, MDN and MDS) but partly also in other zones. This response has been combined with the expansion of irrigated areas. Although the irrigation expansion seems to be an obvious response in very dry zones, where water resources are limited (LUS and MDS), we have seen quite marked drop in the area under irrigation in combination with change of crop choice. Almost all zones show quite pronounced efforts in introduction of cultivation techniques reducing soil erosion. This may be a response to a higher frequency of more intense precipitation leading to water erosion, but also the result of more frequent droughts as a prerequisite of wind erosion over the area. The changes in rainfall patterns are most likely behind the reported focus on field drainage systems, but adoption of this measure seems to be the least notable.

4.4. Future adaptation responses

4.4.1. Cultivation timing

Changes in timing of cultivation (including sowing and harvest) are expected to have minor to moderate effects for all five model crops evaluated by the respondents (Fig. 7). Interestingly the largest changes are expected on the opposite sides of the north–south climate gradient, i.e. ALN and BOR in case of wheat, barley and grassland production and MDM and MDN in case of barley, maize, grassland and grapevine. In general, notable changes towards earlier sowing dates (and consequently of other field operations) are expected in order to avoid hot and dry periods during summer and use as much of the winter precipitation as possible. The anticipation of large shifts in timing of cultivation in the northern zones is probably enhanced by a pronounced prolongation of the growing season that will allow introduction of longer duration cultivars.

4.4.2. Tillage practices

Change in tillage practices under climate change here mostly focused on soil water conservation and protection against soil erosion (both water and wind), as these issues are believed to become increasingly important (Falloon and Betts, 2010). Introduction of water-conserving tillage practices are assumed to be an important adaptation measure especially in case of wheat, barley and to some extent maize in the warm and dry zones (PAN, MDM, MDN and partly MDS and CON), whereas the zones that are expected to experience increase of precipitation (e.g. BOR or ATN) put more stress on erosion protection as soil water reserves are not expected to be replenished during winter months. For grasslands the most notable change will occur in ALN and BOR, where the duration of the growing season will increase leading to enhanced potential productivity that will facilitate changes in tillage practices. Changed tillage practices for soil water conservation are considered likely adaptation responses for grapevine production in MDM, MDS and MDS.

4.4.3. Fertilisation practices

The expected shifts of fertilisation show an interesting north–south gradient with the northernmost zones expecting moderate to major changes in the fertilisation schemes both in arable crops (wheat, barley or maize) and perennials (grassland and partly grapevine). As the potential productivity of northern zones (ALN, BOR, NEM or ATN) is expected to increase due to longer vegetation season, it will also require increased nutrient supply. However, the expected increase in precipitation may lead to higher risk of nitrogen and phosphorus leaching resulting in needs for modification of fertilisation and crop management practices to comply with EU environmental targets. The expectations for changes in fertilisation in drier zones are much lower and only minor changes are expected as far as fertilisation is concerned in MDN, MDS, LUS, ATC and partly PAN in case of barley, maize and grasslands. In case of grapevine the picture is more complex with ATN, CON and MDM expecting larger changes than other zones.

4.4.4. New cultivars

The prospect of adaptation through cultivar changes is obviously smallest for grassland (Fig. 7d), whilst it is expected to be important in case of arable crops and in some zones also for grapevine. The new cultivars are expected to be more important in case of spring barley and grain maize. According to the respondents this measure is thought to be quite pronounced for NEM, ALS, CON, PAN, MDN and MDM.

4.4.5. Crop protection

The expected change in the crop protection efforts is one of the prominent adaptation measures, especially for wheat, barley, maize and partly grapevine. The economic benefit of crop protection and monitoring is quite low for grasslands (as are the risks). However, for wheat, barley and maize major changes in the crop protection schemes are expected, especially in BOR, NEM, ATN, ALS, CON and PAN. This emphasizes the need for pest and disease monitoring as one of the key adaptation responses. The focus on pests and diseases is a consequence of the likely northward spread of pests and diseases from warmer zones under climate change. In addition, in BOR and ATN the expected higher precipitation might result in higher infestation pressure of some "native" diseases (e.g. *Fusarium sp.*). Overall the importance of monitoring systems was mentioned by respondents across all zones with the exception of LUS.

4.4.6. Seasonal weather forecasting

The changed climatic conditions and according to some indications higher probability of unusual weather patterns led most respondents to stress the role of seasonal forecasting as an adaptation tool. The seasonal forecasting is expected to be important in case of field crops and partly also grapevine, whilst in case of grasslands it is given minor priority probably for the same reasons as for phytopathological monitoring. For wheat, barley and maize the largest effect of seasonal forecasting is expected in zones, where relatively large inter-seasonal variations are more likely, i.e. those with higher continentality (e.g. BOR, NEM or PAN) compared to ATN or ATC, and in case of Mediterranean zones (MDM, MDN and MDS) the importance of seasonal forecasts likely result from increasing inter-annual variability in rainfall.

4.4.7. Crop insurance

As crop insurance is seen as a quite effective tool for mitigating the effect of climatic hazards during the growing season, the highest importance has been reported for zones, where the climate impact is expected to be mostly negative. This explains why respondents in the NEM, CON, ALS and especially PAN put large emphasis on this particular adaptation measure, whereas in ATC or LUS this option was not seen as important.

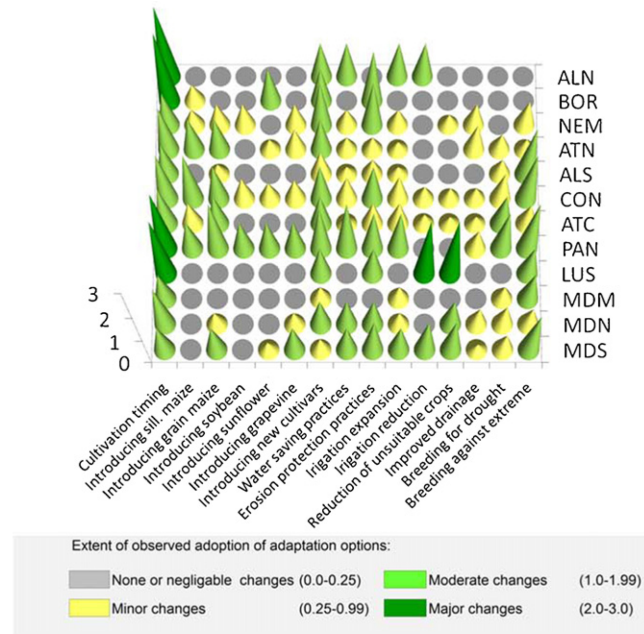

Fig. 6. Observed adaptation responses as reported by respondents for individual environmental zones.

4.5. Improving awareness and adaptation to climate change

Respondents were asked to classify the status of (1) national adaptation strategy for agriculture, (2) awareness of climate change among farmers, (3) awareness of climate change among agricultural advisers, (4) awareness of climate change in government, (5) presence of specific activities to increase awareness among farmers, and (6) type of activities to increase awareness among farmers.

There is a top–down "gradient" in the collective knowledge on climate change impacts on agriculture with a higher level of understanding in governmental offices and a lower knowledge and awareness in case of extension services and individual farmers (Fig. 8). Despite the upsurge of information flow from various sources, the level of awareness seems to be relatively low compared to the level of observed adaptation reported in the survey (Fig. 6). Only in one-third of the countries are the most affected group (farmers) considered to have a good understanding of the consequences of climate change on their enterprise and livelihoods. It also seems that the policy makers in most countries are not sufficiently informed about the risks associated with the climate change impacts for agriculture. This could be a possible explanation of a large discrepancy between the claimed awareness among government officials as almost 2/3 of the countries claim to have medium or good level of information on possible impacts, but only three countries reported an existing agricultural adaptation strategy. Although 75% of responding countries acknowledged activity aimed at increasing farmer awareness, there seems to be quite a long way to go before sufficient level of understanding is reached.

The level of information dissemination and existence of warning systems shows that a lot needs to be done in improving resilience of farming systems across Europe. The survey showed quite large differences between individual countries (and crops) but in general the use of decision support systems (DSS) is lower than expected. Whereas drought seems to be a pervasive problem across all zones and the risks will be higher under a changed climate, only half of the countries have some sort of DSS and only one-fifth of the countries have a nation-wide drought monitoring scheme. The situation is even worse for heat stress and weed management. On the other hand, selection of suitable crops or cultivars, crop protection and fertilisation schemes seems to be quite well supported by existing DSS with farm-based approaches in case of fertilisation and regional approaches in case of the crop protection.

One of the possible explanations of the present state is that the listed factors play an important role in the economy of every farm and direct benefits of DSS is well understood by farmers as it directly affect farm profitability. On the other hand accounting for drought or heat stress is less straight forward, and whilst information on this may be essential for decision makers, farmers are less inclined to demand such information. Surprisingly, in case of irrigation scheduling that has been always seen as one of the most efficient application of DSS, the results of the survey show a rather mixed picture. Whilst in some countries quite sophisticated DSS are applied (mostly in drier zones), in many countries where irrigation is used for wheat, maize, grasslands and grapevine production, there is no DSS system in place. This is in particular worrying, given the projected trends in droughts and irrigation needs.

5. Discussion

5.1. Present climate limitations

In northern countries duration of the growing season, late spring and early autumn frosts and solar radiation availability are typical climatic constraints (Olesen and Bindi, 2002). In these environments the duration of the growing season (frost or snow-free period) limits the productivity of crops. For example in Germany the growing season is 1–3 months longer than in Scandinavian countries (Mela, 1996), but it also varies greatly with the altitude with differences of up to 3 months in Austria (Trnka et al., 2009). The short growing season is the main reason for the lower wheat yields in the Nordic countries (Fig. 1). Moreover, night frosts in late spring or early autumn increase the agricultural risk in these environments as it was shown in our study. The wet conditions along the Atlantic coast (ATN, ATC) and in the mountainous regions (ALS or ALN) causing cold and rainy summers cause yield and quality losses in many arable crops. These wet conditions also affect soil workability and reduce the number of machinery work-days (Brignall and Rounsevell, 1995). This is the main reason for the small area put down to cereals in the British Isles and Alpine countries compared with other regions. Permanent pastures dominate in these areas.

In Mediterranean countries cereal yields are limited by water availability, heat stress and the short duration of the grain-filling period. Permanent crops (olive, grapevine, fruit trees etc.) are therefore more important in this region. These crops are affected by extreme weather events (such as hail and storms), which can reduce or completely destroy yield. Irrigation is important for crop production in many Mediterranean countries due to high evapotranspiration and restricted rainfall. The continental climate of eastern Europe (represented by CON and PAN zones) causing drier conditions and greater amplitude of the annual temperature cycle limits the range of crops that can be grown and the overall productivity. The most productive regions in Europe in terms of climate and soils are located in the great European plain stretching from south-eastern England through France, Benelux and Germany into Poland and include ATC zone and partially also ATN and CON areas. There are additional lowland regions, e.g. the Hungarian plains, where equally favourable soil conditions prevail, but climatic conditions to some extent limit crop production (Fig. 4).

5.2. Vulnerabilities and climate impacts on crops

Many studies have assessed effects of climate change on agricultural productivity in Europe (e.g. Harrison et al., 2000; Maracchi et al., 2005). However, relatively little work has been done to link these results across sectors to identify vulnerable regions and farming systems (Olesen and Bindi, 2002). Such assessments are needed to properly identify needs for change in agricultural policy caused by climate change. However, this is a complex task since many factors, both biophysical and management related, interact. Analysis of farming system responses to climate change is therefore often too complex a task to be handled by models alone. Our approach was a much simpler one, to ask in a semi-quantitative manner knowledgeable experts on their perception of likely vulnerabilities and impacts of climate change for major crops in their geographical area of expertise. This carries some degree of subjectivity, but it has the advantage of being able to cover many more (interacting) factors than is usually handled in model-based impact assessments.

Climate change principally affects agricultural crop production in six ways: (1) directly though effects on increasing CO_2 concentration on crop productivity and resource use efficiencies (Kimball et al., 2002; Ainsworth and Long, 2005), (2) directly through effects of temperature, rainfall, radiation, humidity etc. on crop development and growth (Olesen and Bindi, 2002), (3) indirectly through shifts in suitability of different crops, primarily a northward expansion of warm-season crops (Kenny et al., 1993; Carter et al., 1996; Fronzek and Carter, 2007), (4) directly through damages caused by extreme events such as extreme heat waves, hail and flooding, (5) indirectly through changes in crop nutrition and occurrence of weeds, pests and diseases, and (6) indirectly through environmental pollution (e.g., nitrate leaching) or degradation of the resource base (e.g., soil erosion). Of these six impact pathways, crop models and traditional climate change study methods mostly cover the first three. This gives a bias in impact literature towards mostly direct effects of climate change on crop production, and often leaving out some of the indirect effects, which many may be harmful for production, if their importance increases under climate change.

5.2.1. Impacts on crop productivity

Climate-related increases in crop yields are only expected in northern Europe, while the largest reductions are expected around the Mediterranean and in the south-western Balkans and in southern European Russia (Olesen and Bindi, 2002; Maracchi et al., 2005; Alcamo et al., 2007), which corresponds well with our results. This may not be so surprising, since many of the respondents are probably well aware of this literature on climate change impacts. Even so, the results of the questionnaires in many respects give a more negative picture for arable crops in northern Europe than is often obtained just from crop model simulations (e.g., Easterling et al., 2007). This is partly because some of the negative impacts of climate change may be balanced by the positive effects of increased CO_2, and partly because crop model estimates mostly do not include secondary effects of climate changes on factors like soil erosion, nutrient cycling and crop protection.

In southern Europe, particularly large decreases in yield are expected for spring-sown crops (e.g. maize, sunflower and soybeans) (Audsley et al., 2006). Whilst, for autumn-sown crops (e.g. winter and spring wheat) the impact is more geographically variable, yield is expected to strongly decrease in the most southern areas and increase in the northern or cooler areas (e.g. northern parts of Portugal and Spain) (Santos et al., 2002; Minguez et al., 2007; Olesen et al., 2007). However, these results vary between emission scenarios and climate models (Olesen et al., 2007). Some crops that currently grow mostly in southern Europe will become more suitable further north or in higher altitude areas in the South.

The projections for a range of emission scenarios show a 30–50% increase in suitable area for grain maize production in Europe by the end of the 21st century, including Ireland, Scotland, southern Sweden and Finland (Hildén and Lethtonen, 2005; Olesen et al., 2007).

Many fruit trees are susceptible to spring frosts during flowering. A climatic warming will advance both the date of the last spring frosts and the dates of flowering, and the risk of damage to flower buds caused by late frost are likely to remain largely unchanged (Rochette et al., 2004). Additionally the risk of damage to fruit trees caused by early autumn frosts is likely to decrease. However, there may very well be increased problems with pests and diseases (Salinari et al., 2006).

Grapevine is a woody perennial plant, which requires relatively high temperatures. A climatic warming will therefore expand the suitable areas northwards and eastwards (Jones et al., 2005). A climatic warming is also likely to lead to unsuitable conditions for currently economically important traditional varieties, at least at their current locations.

According to our survey grasslands should not be severely affected, but the response of grasslands to climate change will differ depending on their type (species, soil type, management). As a general rule, productivity of European grassland is expected to increase, where water supply is sufficient (Byrne and Jones, 2002; Kammann et al., 2005). On the other hand an increased frequency of summer droughts will severely affect grassland production in the affected areas.

5.2.2. Weeds, pests and diseases

The majority of the pest and disease problems are closely linked with their host crops. This makes major changes in plant protection problems less likely (Coakley et al., 1999). However, most of the respondents consider higher occurrence of pests and diseases (and partly also weeds) as a major problem. These concerns are more pronounced in cooler zones as the temperature increase is favourable for the proliferation of insect pests, because many insects can then complete a greater number of reproductive cycles (Bale et al., 2002).

Changes in climatic suitability will lead to invasion of weed, pest and diseases adapted to warmer climatic conditions (Baker et al., 2000). The speed at which such invasive species will occur depends on the rate of climate change, the dispersal rate of the species and on measures taken to combat non-indigenous species (Anderson et al., 2004). The dispersal rate of pests and diseases are most often so high that their geographical extent is determined by the range of climatic suitability (Baker et al., 2000). The Colorado beetle, the European cornborer, the Mediterranean fruit fly and karnal bunt are examples of pests and diseases, which are expected to show a considerable northward expansion in Europe under climatic warming with some indication that this process has already begun (Trnka et al., 2007).

5.3. Adaptation to climate variability and climate change

To avoid or at least reduce negative effects and exploit possible positive effects, several agronomic adaptation strategies for agriculture have been suggested. Studies on the adaptation of farming systems to climate change need to consider all the agronomic decisions made at farm level (Kaiser et al., 1993). Autonomous adaptation measures are mostly short-term adjustments include efforts to optimise production without major system changes, and which can be developed and implemented independently of most other sectors. On the other hand larger changes will require planning and implementation at society level involving a range of sectors and stakeholders (e.g., policy, research, water, land planning).

5.3.1. Autonomous adaptation

The key autonomous adaptation options were included in our survey (Fig. 7) and almost all were considered important, including changes in varieties, sowing dates and fertiliser and pesticide use (Ghaffari et al., 2002; Alexandrov et al., 2002; Tubiello et al., 2000; Chen and McCarl, 2001; Trnka et al., 2004). In particular, in southern Europe short-term adaptations may include changes in crop species (e.g. replacing winter with spring wheat) (Minguez et al., 2007), changes in cultivars and sowing dates (e.g. for winter crops, sowing the same cultivar earlier, or choosing cultivars with a longer growth cycle; for summer irrigated crops, earlier sowing for preventing yield reductions or reducing water demand (Olesen et al., 2007; Kaukoranta and Hakala, 2008). This partly agrees with our results, which show a large emphasis on short-term adaptation options in northern zones (BOR, ALN).

There are many plant traits that may be modified to better adapt varieties to increased temperature and reduced water supply (Sinclair and Muchow, 2001). The use of early ripening fruit tree species may reduce water consumption, as proper management practices may be applied to orchards to improve adaptation (Rossi, 2006). However, the effectiveness of such traits depends on whether there is simultaneous change in climatic variability, and a combination of traits may be needed to stabilise yield in poor years, without sacrificing yield in good years (Porter et al., 1995; Sinclair and Muchow, 2001). The relative scepticism towards these "climate proof" cultivars was reflected in our survey by a relatively low score to this measure (Fig. 7). In northern Europe new crops and varieties may be introduced only if improved varieties will be introduced to respond to specific characteristics of the growing seasons (e.g. day length) (Hildén and Lethtonen, 2005; Peltonen-Sainio et al., 2009).

5.3.2. Planned adaptation

The long-term or planned adaptations refer to major structural changes to overcome adversity caused by climate change. This involves changes in land allocation and farming systems, breeding of crop varieties, new land management techniques, etc. This involves changes of land use that result from the farmer's response to the differential response of crops to climate change. The changes in land allocation may also be used to stabilise production. This means substitution of crops with high inter-annual yield variability (e.g. wheat or maize) by crops with lower productivity but more stable yields (e.g. pasture or sorghum). Crop substitution may be useful also for the conservation of soil moisture. However, there are limits to the effectiveness of this option as reflected by the survey respondents. Other examples of long-term adaptations include breeding of crop varieties, new land management techniques to conserve water or increase irrigation use efficiencies, and more drastic changes in farming systems (including land abandonment). However, increasing the supply of water for irrigation may not be a viable option in much of southern Europe, since the projections show a considerable reduction in total runoff (Lehner et al., 2006).

5.3.3. Farm scale adaptation

The farm is typically the entity at which adaptation to climate change and climatic variability must take place through introduction of new management methods and technologies. Because of the complexities of processes, management and inter-relationships of land use within a farm, studies on farming systems require a holistic approach (Rivington et al., 2006). Climate change will not only affect crop yield, but total farm-level production through effects on altered carbon and nitrogen flows resulting from changed crop and residue quality, crop resource use, or mineralisation of soil organic matter (Dueri et al., 2006). Adaptation will have to deal with all of these issues, and the links with water availability may be among the most important ones, affecting the need for improving irrigation

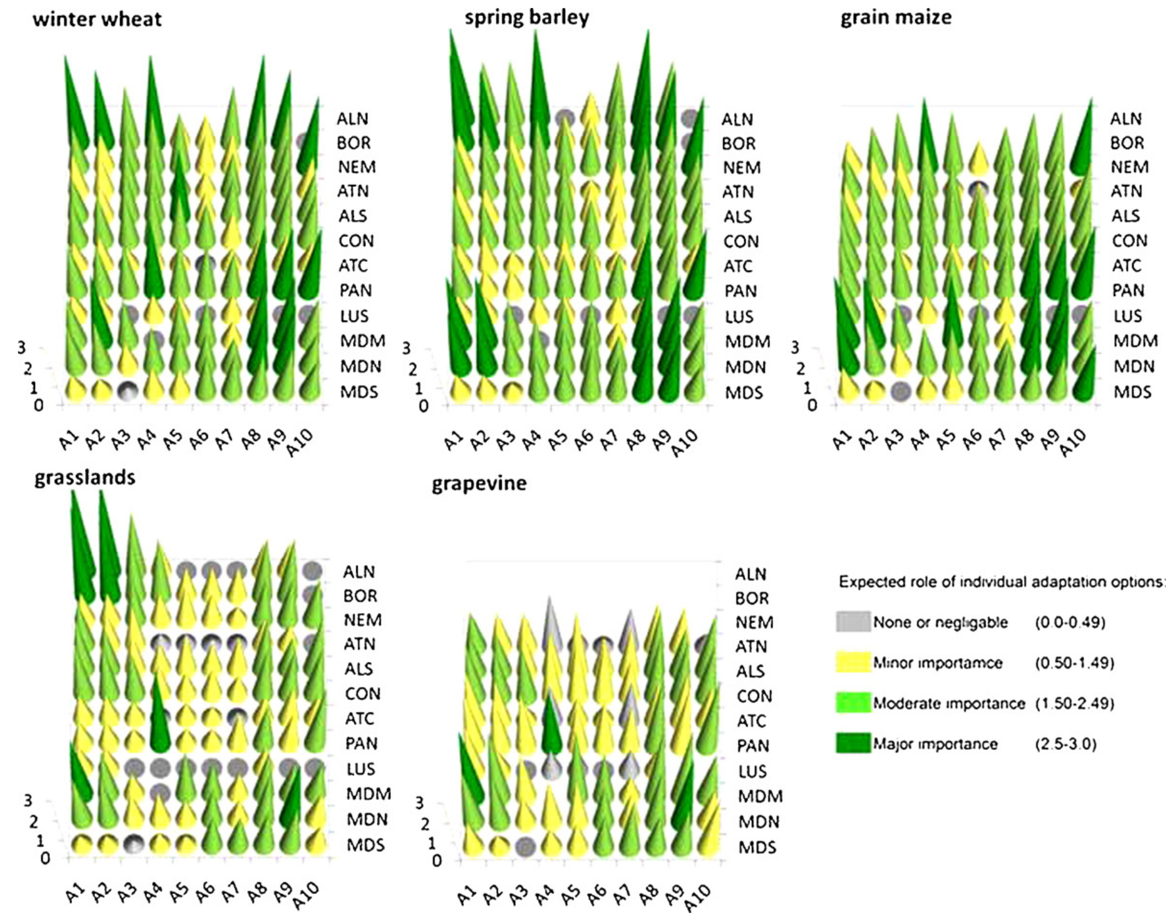

Fig. 7. Expected importance of adaptation measures under the expected climate conditions for individual crops. Legend: A1 cultivation timing; A2 new tillage practices; A3 modification to the fertilisation practices; A4 modification of crop protection; A5 introduction of new "climate-proof" cultivars; A6 soil water conservation practices; A7 focus on protection from soil erosion; A8 operational monitoring of pests and diseases; A9 seasonal agrometeorological forecast; A10 introduction of crop insurance.

efficiencies (Tavakkoli and Oweis, 2006) or the need for terracing (Wadsworth and Swetnam, 1988; Fuhrer et al., 2006).

Our survey indicates that there is a medium high awareness in the farmer community regarding climate change and substantial amount of activity informing the farmers (Fig. 8). On the other hand co-ordinated government policies supporting higher resilience of farming sector to climate change are either missing or in preparation.

Changes in farming systems structure at regional or larger scales may also play a fundamental role in the adaptation of European agriculture to climate change. As can be seen from the presented results (Figs. 5–7) there are rather pronounced differences in the responses for individual environmental zones and the same was pointed by other studies (e.g., Berry et al., 2006).

5.3.4. Increasing resilience to change

Some of the recent studies taking into account potential impacts, adaptive capacity, and the vulnerability of farmer livelihoods indicate the agricultural sector in the Mediterranean region as vulnerable under most climate change scenarios (Metzger et al., 2006). In accordance with this study we found that the Mediterranean region shows very little signs of positive impact of climate change on farming, as well as comparatively smaller adaptive capacity that is somewhat reflected in those adaptations already observed. On the other hand the respondents view the northern and north-western parts of Europe as the area, where the main gains (but also major challenges) are situated. However, the areas that came out as the most negatively affected in terms of changing conditions for crop production belong to the Pannonian (PAN) environmental zone rather the Mediterranean, which is worrying given the role that agriculture still plays in the national economies of countries located within the PAN zone (e.g., Romania, Bulgaria, Hungary, Serbia). Also parts of Austria, Czech Republic and Slovakia are expected to be highly negatively affected.

So far, research on climate change impacts in agriculture has given little emphasis to changes in frequency of extreme events. However, the impacts of increased climate variability on plant productivity are likely to increase yield losses above those estimated from changes in mean climate only (Porter and Semenov, 2005). This is primarily linked with changes in the frequency of extreme heat waves and changes in rainfall patterns, including more intensive precipitation events and longer dry periods. Changes in climate variability may be particularly difficult for many farmers to adapt to, and adaptation strategies to cope with variability may be different than from those dealing with changes in mean climate. Strategies for adapting to increased variability may include measures to avoid periods of high stress or measures that increase resilience of the system by adding diversity in the crop rotation and improving soil and water resources (Reidsma and Ewert, 2008).

Several adaptation measures may be used to increase resilience to climate change in cropping systems. However, when it relates to soil and water resources, building resilient systems may require long-term planning and changes already now in anticipation of climate change. An example of this can be illustrated by the link between climate change and soil degradation, which is one of the

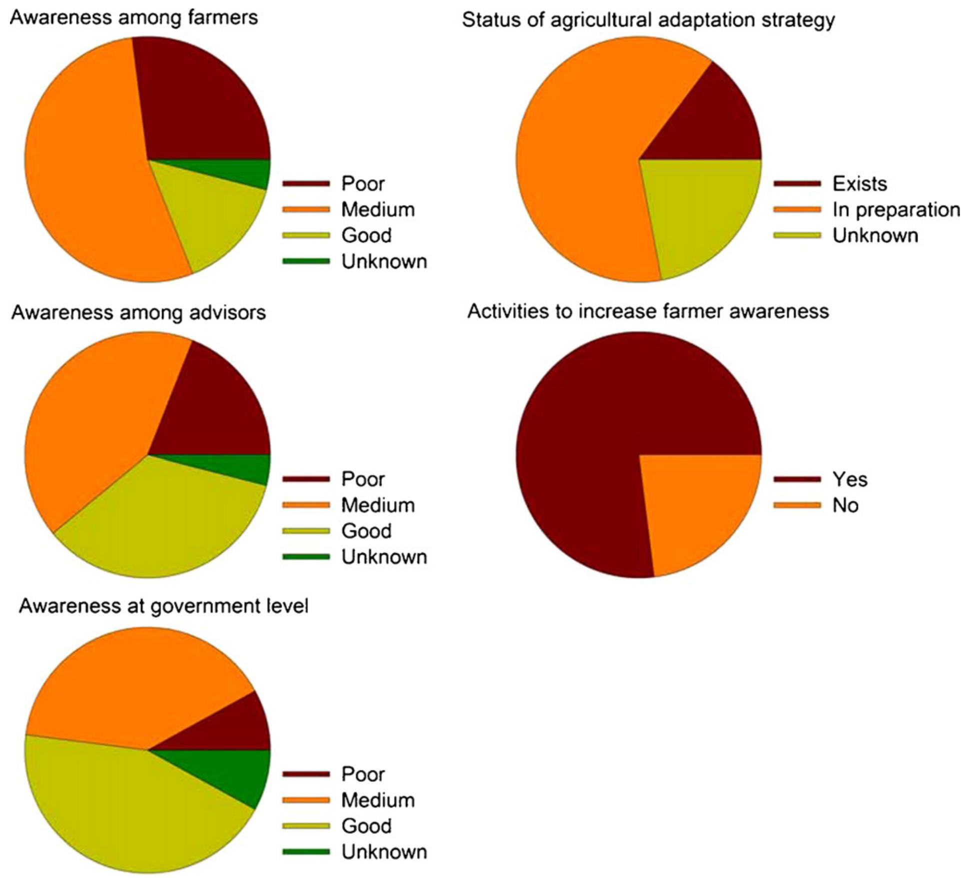

Fig. 8. Reported level of climate change awareness among farmers, agriculture advisors and government officials in 26 countries and the status of agriculture adaptation strategy and education programs for farmers.

greatest threats to global food production (Lal et al., 2007). Most of the processes causing soil degradation are enhanced by climate change, being promoted by higher temperatures, more intense rainfall and longer drought periods, which lead to lower soil carbon stocks, increased soil erosion and salinization (Tubiello et al., 2007). Yet, higher soil carbon contents and better soil structure will be critical for cropping systems to cope with increased climate variability. There is clearly a need within research, farmer advice and policy making to focus more on those aspects of agricultural systems that build resilience.

6. Implications and perspectives

The results of the present study indicate not only most vulnerable areas but also those that might profit from the expected changes. Surprisingly the expected impacts (both positive and negative) of climate change in Mediterranean are in several cases smaller than those expected for northern or central Europe. This is partly explained by the possibilities for shifting some of the crop cultivation into the winter season in the Mediterranean countries in a warmer climate (Minguez et al., 2007). Probably the bleakest expectations could be found in responses from continental climate of Pannonian environmental zone. Still the adaptation strategies should be introduced to reduce negative effects and exploit possible positive effects of climate change. Both short-term adjustments (e.g. changes in crop species, cultivars and sowing dates) and long-term adaptations (e.g. water management, land allocation, farming systems and institutions) are considered as important across most zones. However, the differences in climate exposure, sensitivity, and adaptive capacity will differently affect agroecosystems across Europe. The projected changes and the perceptions of impacts and adaptation as seen from the questionnaires have some implications for agricultural and environmental policy, for research and for development of the agricultural sector.

Policy will have to support the adaptation of European agriculture to climate change by encouraging resilience of cropping systems to increased climate variability and to more extreme weather conditions. This includes investing in monitoring schemes, early warning systems and crop breeding. Policy will also need to be concerned with agricultural strategies to mitigate climate change through a reduction in emissions of methane and nitrous oxide, an increase in carbon sequestration in agricultural soils and the growing of energy crops to substitute fossil energy use, and this needs to be linked to the needs for adaptation to climate change (Smith and Olesen, 2010). The policies to support adaptation and mitigation to climate change will need to be linked closely to the development of agri-environmental schemes in the EU Common Agricultural Policy.

Research will have to deal with some "unknown aspects" that due to their complexity have not yet been studied in detail. These include the effect on secondary factors of agricultural production (e.g. soils, weeds, pests and diseases), the effect on the quality of crop and animal production, the effect of changes in frequency of isolated and extreme weather events on agricultural production, and the interaction with the surrounding natural ecosystems. It should also be noted that for obvious reasons most studies on climate change impacts have so far focused on crops. However, some livestock production systems, especially those involving grazing systems or use of fresh fodder, may be severely affected by climate change, and more studies on these systems are warranted.

There is a considerable need for an increased attention on regional studies of impacts and adaptation to climate change in agriculture, since effects and responses have been shown by our study to be regionally specific depending on interactions with soils, current climate and cropping systems. These studies should include assessments of the consequences on current efforts in agricultural policy for a sustainable agriculture that also preserves environmental and social values in the rural society. The research on adaptation in agriculture has not yet provided a generalised knowledge on the adaptive capacity of agricultural systems across a range of climate and socioeconomic futures. There is also a considerable need to better estimate the costs of various adaptation measures, and adaptation studies have to move from looking at potential adaptation to adoption, taking into account the complexity of farm-level decision-making, diversities at different scales and regions (including the entire food chain), and time-lags in responses and biophysical, economic, institutional and cultural barriers to change.

The adaptation to climate change has in particular to be factored in as part of the ongoing technological development in agriculture, including plant breeding (including molecular techniques), irrigation management, application of information and communication technology etc. However, such technologies should maintain and possibly improve soil quality and water resources, which are essential for improving resilience to climate change in cropping systems. In some cases such adaptation measures would make sense without considering climate change, because they help to address current climate variability. In other cases, the measures must be implemented in anticipation of climate change, because they would not be sufficiently effective if implemented as a reaction to climate change.

7. Conclusions

Analysis of national crop yields and of the questionnaire survey shows large differences in vulnerabilities to current climate and climatic variation across Europe. Cool temperatures and short growing seasons are main limitations in northern Europe, whereas high temperatures and persistent dry periods during summer limits crop production in southern Europe. There are clear trends on increasing temperature affecting crop production and crop choice throughout Europe, with increasing frequency of droughts negatively affecting crop yield in southern and central Europe. There are also indications of increasing yield variability linked with higher frequencies of heat waves and of both droughts and persistent wet periods. Farmers are already adapting to changed climate with the area of silage and grain maize expanding northwards. Other currently observed adaptation to climate change includes changes in timing of cultivation, variety choice, water saving techniques, irrigation and breeding.

There are large regional variations in expected impacts of climate change on crop cultivation and crop productivity in Europe by 2050. The expected impacts, both positive and negative, are just as large in northern Europe as in the Mediterranean countries, and this is largely linked with the possibilities for effective adaptation to maintain current yields. The most negative effects were found for the continental climate in the Pannonian zone, which includes Hungary, Serbia, Bulgaria and Romania. This region will suffer from increased incidents of heat waves and droughts without possibilities for effectively shifting crop cultivation to other parts of the years. A wide range of adaptation options exists in most European regions to mitigate many of the negative impacts of climate change on crop production in Europe. However, when all effects of climate change are considered, including crop yields, soil fertility, pesticide use, and nutrient runoff, effects of climate change are still mostly negative in most regions across Europe.

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