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Adaptation to climate change and climate variability in European agriculture: The importance of farm level responses

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ABSTRACT

Climatic conditions and hence climate change influence agriculture. Most studies that addressed the vulnerability of agriculture to climate change have focused on potential impacts without considering adaptation. When adaptation strategies are considered, socio-economic conditions and farm management are often ignored, but these strongly influence current farm performance and are likely to also influence adaptation to future changes. This study analysed the adaptation of farmers and regions in the European Union to prevailing climatic conditions, climate change and climate variability in the last decades (1990–2003) in the context of other conditions and changes. We compared (1) responses in crop yields with responses in farmers' income, (2) responses to spatial climate variability with responses to temporal climate variability, (3) farm level responses with regional level responses and (4) potential climate impacts (based on crop models) with actual climate impacts (based on farm accountancy data). Results indicated that impacts on crop yields cannot directly be translated to impacts on farmers' income, as farmers adapt by changing crop rotations and inputs. Secondly, the impacts of climatic conditions on spatial variability in crop yields and farmers' income, with generally lower yields in warmer climates, is different from the impacts of temporal variability in climate, for which more heterogeneous patterns are observed across regions in Europe. Thirdly, actual impacts of climate change and variability are largely dependent on farm characteristics (e.g. intensity, size, land use), which influence management and adaptation. To accurately understand impacts and adaptation, assessments should consider responses at different levels of organization. As different farm types adapt differently, a larger diversity in farm types reduces impacts of climate variability at regional level, but certain farm types may still be vulnerable. Lastly, we observed that management and adaptation can largely reduce the potential impacts of climate change and climate variability on crop yields and farmers' income. We conclude that for reliable projections of the impacts of climate change on agriculture, adaptation should not be seen anymore as a last step in a vulnerability assessment, but as integrated part of the models used to simulate crop yields, farmers' income and other indicators related to agricultural performance.

1. Introduction

Climate change is considered as one of the main environmental problems of the 21st century. The IPCC fourth assessment report states that global average surface temperature has increased by $0.74 \pm 0.18\,^{\circ}$C in the last century and is projected to increase by another 1.1–6.0 °C in this century (IPCC, 2007b). Rahmstorf et al. (2007) compared scenarios with observations and showed that the measured increase is in the upper range of the projections, implying that we should prepare for a 6.0 °C increase towards the end of this century. Eleven of the last 12 years from 1995 to 2006 belong to the 12 warmest years since systematic climate observations began in 1850. In Europe, not only warmer conditions have been observed, but also changes in extreme weather events. For example, the European heatwave during the summer of 2003 was extremely exceptional for current climate conditions and statistically very unlikely to occur (Schar et al., 2004). Only if one assumes that the present climate regime has already experienced a shift towards increased variability, the occurrence of this heatwave can be reasonably explained. It is projected that Europe will experience a pronounced increase in the incidence of such heatwaves and related droughts.

The heatwave of 2003 had a considerable impact on crop productivity (Ciais et al., 2005). Assessments of climate change impacts

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on European agriculture suggest that in northern Europe, crop yields increase and possibilities for new crops and varieties emerge (Ewert et al., 2005; IPCC, 2007a; Olesen and Bindi, 2002). In southern Europe, adverse effects are expected. Here, projected increases in temperatures and in water shortage reduce crop yields and the area for cropping. This will affect the livelihood of Mediterranean farmers (Metzger et al., 2006; Schröter et al., 2005). According to the IPCC definition, the extent to which systems are vulnerable to climate change depends on the actual exposure to climate change, their sensitivity and adaptive capacity (IPCC, 2001). Exposure and sensitivity determine the potential impacts that occur given the projected climate change without considering adaptation. The actual impact is the impact that remains after accounting for adaptation. The adaptive capacity refers to the ability to cope with climate change, including climate variability and extremes, in order to (1) moderate potential damages, (2) take advantage of emerging opportunities, and/or (3) cope with its consequences. Most quantitative studies that address the vulnerability of agricultural systems have focused on exposure and sensitivity, while adaptive capacity is often highly simplified. Realistic adaptation processes are not well understood and therefore hard to quantify (Smit et al., 2001). Progress has been made in recent years (IPCC, 2007a), but the complexity of relationships and the resulting dynamic behavior remains difficult to unravel.

The main objective of this study was to assess how adaptation influences the impact of climate change and climate variability on European agriculture. This paper synthesizes results from a number of empirical analyses on the role of adaptation under climatic change (Reidsma, 2007). The synthesized empirical analyses combined agricultural data at farm and regional level with climatic and socio-economic data to improve insights in adaptation of agriculture to climate change. Both impacts on crop yields and on farmers' income were considered. Results should allow improving assessment models to project climate change impacts on agriculture. In this paper we do not make explicit future projections of climate change impacts; rather we discuss the implications of our results for these projections.

2. Theoretical background and framework for analysis

Impacts of climate change on crop productivity are generally assessed with crop models (Easterling et al., 2007). In most crop modelling studies, farmers' responses to climate change are purely hypothetical and either no adaptation or optimal adaptation is assumed (e.g. Rosenzweig and Parry, 1994). Easterling et al. (2003) made a first attempt to model agronomic adaptation more realistically, proposing a logistic growth function to describe the adaptation process over time. Meza and Silva (2009) recently linked a crop model with an economic model to assess an optimal dynamic adaptation process. Nevertheless, adaptation strategies are restricted to the few that can be simulated with crop models, and how agricultural adaptation varies spatially is not assessed to date. Mendelsohn and Dinar (1999) suggest that climatic conditions have a relatively smaller impact on farmers' income (i.e., net income/farm value) than on crop productivity as simulated by crop models. Their cross-sectional analysis implicitly includes adaptation, both at crop and farm level. Since the relative profitability of crops differs across climates, farmers can adapt by optimizing the crop mix. This type of adaptation is accounted for by analyzing the impacts on farmers' income rather than crop yields.

The first studies that considered adaptation quantitatively in impact assessments, developed regional indices determining adaptive capacity based on general socio-economic conditions (Brooks et al., 2005; Haddad, 2005; Schröter et al., 2003; Yohe and Tol, 2002). The regional scale adaptive capacity index that was developed for Europe, an aggregated index based on for example GDP per capita and R&D expenditure, suggests that Mediterranean regions have a lower generic adaptive capacity compared to northern European regions (Metzger et al., 2006; Schröter et al., 2003). As also sensitivity to climate change is projected to be more severe in Mediterranean regions (Ewert et al., 2005; Olesen and Bindi, 2002), the vulnerability of the agricultural sector is projected to be highest in these regions (Metzger et al., 2006; Schröter et al., 2005).

Adaptation in agriculture is clearly dependent on regional socio-economic conditions, but for a thorough understanding of agricultural adaptive capacity, also sector and farm specific conditions should be taken into account. For several regions vulnerability or adaptive capacity indices specific for agriculture are developed (Eakin et al., 2006; Nelson et al., 2005). However, there is little empirical evidence about the importance of the different factors from which these indices are derived. Furthermore, adaptation processes that occur at different aggregation levels and relate to different indicators (e.g. yields of various crops, farmers' income) cannot be captured with one regional adaptive capacity index (Füssel, 2007).

Adaptations in agriculture vary depending on the climatic stimuli (to which adjustments are made), different farm types and locations, and the economic, political and institutional conditions (Bryant et al., 2000; Smit and Skinner, 2002). They include a wide range of forms (managerial, technical and financial), scales (local, regional and global) and actors (farmers, industries and governments). Adaptation options can be grouped into four main categories (Smit and Skinner, 2002): (1) farm production practices, (2) farm financial management, (3) technological developments and (4) government programs and insurance.

The scale at which climate impacts and adaptations are assessed is thus of major importance. The crop models that are generally used to assess climate impacts on crop productivity are developed for simulations at field level. Crop models strongly emphasize biophysical factors, such as climate and soil conditions. Validation of these models for application at regional level remains unsatisfactory (Tubiello and Ewert, 2002), although recent progress in large-area crop modelling is acknowledged (Challinor et al., 2009). The dynamic nature of climatic effects is well understood for potential, water and nitrogen limited growth and yield (e.g. van Ittersum et al., 2003; Fig. 1). Actual farm yields, however, are also affected by other factors, such as pests and diseases, which depend on farm management and regional conditions. How these influence climate impacts is not well understood.

Decisions regarding management and adaptation herein are made at the farm level. Potential impacts of climate change and climate variability on crop yields at field level can be assessed with crop models. However, for projections of actual impacts at higher aggregation levels, the farm level should be considered to take farm management and adaptation into account. Crop yields influence farmers' income, but goals of farmers regarding income will also affect crop yields. In this study we considered that farm performance (at farm and regional level) is influenced by two groups of factors related to (1) farm(er) characteristics and (2) regional conditions, such as biophysical, socio-economic and policy factors (Fig. 2).

This study assessed the adaptation of farmers and regions in the EU15[1] to climatic conditions, climate change and climate variability in the last decades (1990–2003). We compared (1) responses in crop yields with responses in farmers' income, (2) responses to spatial climate variability with responses to temporal climate variability, (3) farm level responses with regional level responses and (4) potential climate impacts (based on crop models) with actual cli-

[1] The EU15 comprises the 15 member countries of the European Union before the extension in 2004.

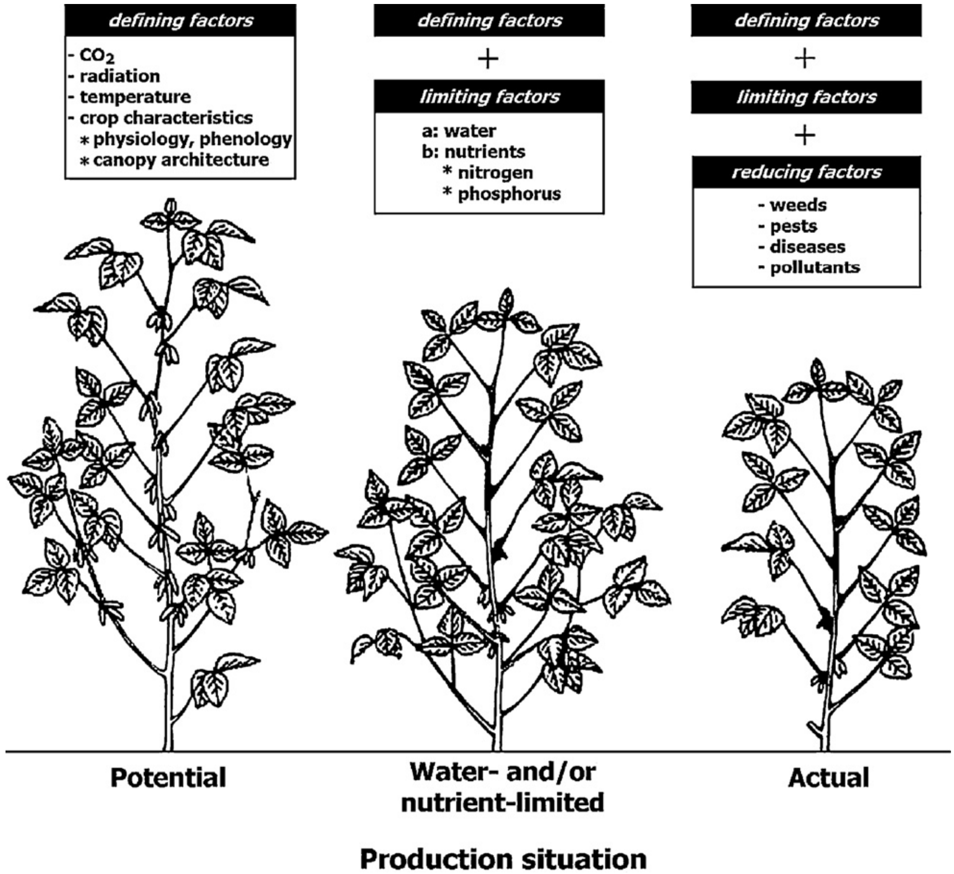

Fig. 1. A hierarchy of growth factors, production situations and associated production levels (*Source*: van Ittersum et al., 2003).

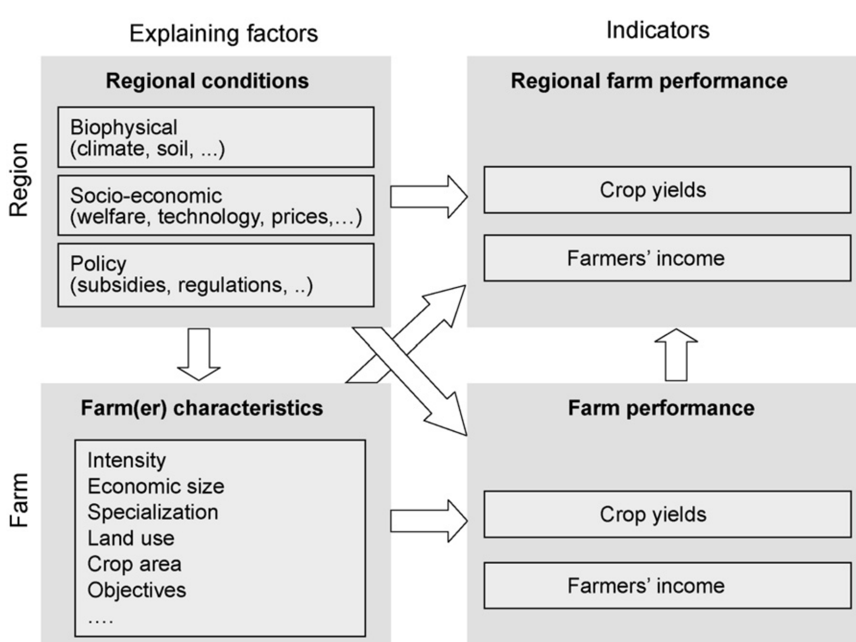

Fig. 2. Summary overview of the investigated relationships. Impacts of climate change on farm and regional agricultural performance are not only influenced by biophysical conditions, but also by other regional conditions and farm characteristics, which influence management and adaptation. Relationships are analysed spatially and temporally.

mate impacts (based on farm accountancy data). In the next section we will further elaborate on this.

3. Data and methods

This study synthesizes results from a number of empirical studies on impacts and adaptation to climatic change. This section explains data and methods that were used in these empirical studies. For further elaboration, the reader is referred to Reidsma (2007) and other cited references.

3.1. Data sources and data processing

3.1.1. Observed crop yields and farm characteristics

Farm and regional level data were obtained from the Farm Accountancy Data Network (source: FADN-CCE-DG Agri and LEI; http://ec.europa.eu/agriculture/rica/) from 1990 to 2003. The FADN provides extensive data on farm characteristics, inputs and outputs of individual farms throughout the EU15 (Table 1). Data have been collected annually since 1989; for East Germany, Finland and Sweden since 1995. They have been used to evaluate the income of farmers and the consequences of the Common Agricultural Policy. In total, 100 HARM[2] regions are distinguished with more than 50,000 sample farms. Data of individual farms can be used for analysis in specific years, but for temporal analyses aggregation into farm types is required. The exact geographic location of the sample farms is not known for privacy reasons, and hence, individual farms cannot be followed over time. Farms were aggregated into farm types based on specialization/land use, economic size and intensity; important farm characteristics that influence farm performance (see Section 4; Andersen et al., 2007; Reidsma et al., 2007). The farm typology was developed in the EU-funded project SEAMLESS (Andersen et al., 2006; van Ittersum et al., 2008).

3.1.2. Simulated crop yields

Within the MARS project (Monitoring Agriculture with Remote Sensing, JRC-Agrifish MARS STAT; www.marsop.info) potential and water limited yields of various crops are estimated throughout Europe. The Crop Growth Monitoring System (CGMS; de Wit et al., 2005; Lazar and Genovese, 2004) estimates yearly regional crop yields since 1975 using the widely applied and validated crop model WOFOST (Rabbinge and van Diepen, 2000; Supit et al., 1994; Wolf and van Diepen, 1995). Potential and water limited crop yields are simulated for each suitable land unit, represented by a unique combination of soil, grid (50 km × 50 km) and administrative unit. Simulated yields of grain maize and soft wheat from 1990 to 2003 were aggregated to HARM regions and used in the analyses to compare with observed yields (Reidsma and Ewert, 2008; Reidsma et al., 2009b).

3.1.3. Climate data

Monthly temperature and precipitation data from 1990 to 2003 were also obtained from the MARS project. Depending on the analysis, the data were averaged for different periods in the year, representing the main growing period of the crops considered. MARS data were obtained per grid cell and averaged per HARM region (Reidsma et al., 2009c). For the spatial analysis climate data based on New et al. (2002) were used (Reidsma et al., 2007). These data were available at a higher resolution ($10' \times 10'$) and were averaged in the same way as those from the MARS project.

[2] HARM is the abbreviation of the harmonized division created by the Dutch Agricultural Economic Institute (LEI). It gives the opportunity to compare the different regional divisions of the EU15 used by Eurostat (NUTS2) and FADN.

3.2. Impacts on crop yields and in farmer's income

Climatic conditions, socio-economic conditions and farm management do not only change over time, but also vary spatially. Therefore, assessments of climate change impacts can be improved using insights from spatial (i.e., cross-sectional) analyses. We used farm level data from the year 2000 combined with data on climatic and socio-economic conditions (Table 1), to assess the impact of farm characteristics, climatic and socio-economic conditions on crop yields and farmers' income across the EU15. As reported in Reidsma et al. (2007) a multilevel statistical analysis was performed to account for regional differences in the studied relationships. Farm characteristics considered were intensity in fertilizer use and crop protection, irrigated area, economic size, grassland and permanent cropping area (both referring to the specialization of the farms in which arable crops are grown), crop area, and whether a farm was organic or not. Biophysical conditions were represented by the possible location of the farm in a less-favoured area (LFA) or at higher altitudes (>600 m). Climatic and socio-economic conditions were included at regional level. For climatic conditions (temperature and precipitation) models were tested with and without a quadratic term.

In order to visually compare the impacts of these factors on yields of soft wheat, grain maize, barley, sugar beet, potato and on income variables, the *t*-values were used to represent the relative significance of the impact. The average of the *t*-values of the five crops was used to generalize impacts on crop yields. Analyses focusing on wheat yields (Reidsma and Ewert, 2008), maize yields (Reidsma et al., 2009b) and outputs regarding these and other arable crops (Reidsma et al., 2009a) were considered in the interpretation of results. Two measures of farmers' income were used: farm net value added per hectare (fnv/ha) and farm net value added/annual work unit (fnv/awu). Fnv/ha measures economic performance per unit of land (i.e., land productivity) and a relationship with crop yields can be expected. Fnv/awu (i.e., labour productivity) is a measure that enables comparison of farmers' income directly to GDP per capita and can therefore relate farm performance to general socio-economic performance.

3.3. Impacts of spatial and to temporal climate variability

The spatial analyses based on farm level data give insights in responses to spatial climate variability. Data at farm type level were used to analyse temporal variability and trends in crop yields and farmers' income. Farm types were based on farm characteristics that proved to be of major importance in the spatial analysis: (economic) size, intensity and land use (Reidsma et al., 2009c). Responses of crop yields and farmer's income to temporal variability were assessed by three measures:

(1) *Trend*: Trends over 1990–2003 were estimated using linear regression models relating indicators of farm performance to time. The coefficients of the trends were used for analyses estimating the impact of farm characteristics and climatic conditions on trends in farm performance indicators (Reidsma et al., 2009c). The trend gives an indication of the longer term adaptation to changes.
(2) *Variability*: The relative variability in crop yields or farmers' income along the linear trend from 1990 to 2003, was used as an indicator of stability (Reidsma et al., 2009c). The stability gives an indication of short-term adaptation to (variability in) a combination of factors.
(3) *Adaptive capacity*: The adaptive capacity here refers to the capacity to reduce the potentially negative impacts of higher temperatures (and associated droughts) in the period 1990–2003.

Table 1
Data description and sources.

Variable	Description	Source[a]
Farm performance		
Crop yield	Actual crop (soft wheat, grain maize, barley, sugar beet or potato) yield (tons/ha)	1
Fnv/awu	Farm net value added[b]/annual work units[c] (€); labour productivity	1
Fnv/ha	Farm net value added/hectare (€); land productivity	1
Farm characteristics		
Irrigated area	Irrigated percentage of utilized agricultural area (%)	1
Fertilizer intensity	Expenditures on fertilizers and soil improvers per hectare (€)	
Protection intensity	Expenditures on crop protection products per hectare (€)	1
Economic size	Economic size[d] (ESU)	1
Permanent crop area	Permanent cropping area/utilized agricultural area	
Grassland area	Grassland area/utilized agricultural area	
Crop area	Crop area (of crop considered)/total arable area	1
Organic	Farm is organic	1
Altitude	Farm is located > 600 m; indication of impact of topography	1
LFA	Farm is located in less-favoured area; indicating less-favourable biophysical and/or socio-economic conditions	1
Subsidies/ha	Total subsidies/utilized agricultural area (€)	1
Regional conditions		
Temperature	Mean temperature (°C) of the main growing season (months differ per analysis)	2, 3
Precipitation	Mean precipitation (mm) of the main growing season (months differ per analysis)	2, 3
Socio-economic	Socio-economic conditions, based on the macro-scale adaptive capacity index	4
Simulated yields		
Potential crop yield	Simulated potential crop yield (tons/ha); CGMS	3
Water limited crop yield	Simulated water limited crop yield (tons/ha); CGMS	3

[a] (1) FADN; (2) New et al. (2002); (3) MARS; (4) Schröter et al. (2003); (1 = farm level; 2, 3, 4 = regional level).
[b] Corresponds to the payment for fixed factors of production (land, labour and capital), whether they are external or family factors. As a result, holdings can be compared irrespective of the family/non-family nature of the factors of production employed. Fnv = total output − total intermediate consumption + balance current subsidies and taxes − depreciation.
[c] One Annual Work Unit (AWU) is equivalent to one person working full-time on the holding.
[d] The economic size is determined on the basis of the overall standard gross margin of the holding. It is given in European Size Units (ESU); one ESU corresponds to a standard gross margin of €1200.

Time series data from 1990 to 2003 were used to assess trends and the relative variability along the trend of crop yields (soft wheat, grain maize, barley, sugar beet and potato) and farmer's income (fnv/ha, fnv/awu) at farm type and regional level (Reidsma et al., 2009c). Trends and relative variability were also estimated for explanatory variables (Table 1). Regression models were used to analyse the impacts of explanatory variables on the trends and relative variability of crop yields and farmers' income. In order to assess the relative impact of different variables on trends and variability in farm performance indicators, the elasticity at the mean was calculated. Comparing elasticities gave slightly different results than comparing relative significance (as for spatial variability, Section 3.2), but conclusions on relative impacts were the same. For comparison with spatial variability, the independent variables on the *x*-axis were ranked in the same order. Due to data availability and model type, the included variables slightly differed. No time series were available for the indicator on socio-economic conditions, while organic, LFA and altitude are factors that cannot be averaged per farm type or region; subsidies/ha were included as indicator of the policy environment. Elasticities for temperature and precipitation were not calculated at the mean, but at the 25th and 75th percentile, to account for the quadratic term. At the farm level, the intensity, economic size, permanent cropping and grassland area referred to farm type dimensions, and the parameters in the models referred to shifts between farm type dimensions. For comparison, elasticities were calculated by using values related to the farm type dimensions. For example, a low intensity farm has a farm return of <€500/ha, and a high intensity farm of €3000/ha. The parameter for fixed effects refers to the change between these values, and the mean can be assumed to be €1750/ha, based on which elasticities can be calculated.

The adaptive capacity was based on results from a frontier analysis assessing interactions between climate and management factors and their impact on total production (Reidsma et al., 2009a). This study allowed to identify farm characteristics, climatic and socio-economic factors that could reduce the potentially negative impact of higher temperatures on farm performance, based on the interaction between temperature and these factors. Analyses were performed for eight regions: Greece, Italy, Spain, France, Germany, Benelux, UK and Scandinavia. Factors reducing the impact of precipitation could also be considered as adaptive capacity indicators, but in most cases the impact of average precipitation was not significant. Droughts were generally better represented by average temperature than average precipitation. As for other temporal analyses, the relative impact was measured by the elasticity at the mean. The original analysis included more factors, but here only the ones similar to other analyses are presented. Note that temperature is in fact the quadratic term, as all presented estimates are from the interactions with temperature. For the interpretation of results also the analyses estimating the impact of different variables on wheat yields (Reidsma and Ewert, 2008) and on maize yields (Reidsma et al., 2009b) were considered.

3.4. Impacts at farm and at regional level

Different farms respond differently to climate variability and climate change. At farm level, some factors, like farm intensity, size and land use, can give some indication of the capacity to adapt. However, in different regions the impact of these factors may be different and therefore difficult to generalize (Reidsma et al., 2009a).

The vulnerability of food production to climate change is generally investigated at regional level; the impacts at farm level are not necessarily relevant for studies at regional and higher aggregation levels. The way the farm level influences the regional level is very relevant, however. As reported in Reidsma and Ewert (2008), we analysed the influence of regional farm diversity on the impacts of climate variability on regional wheat yield variability. Important here is how wheat yield variability at farm level differed

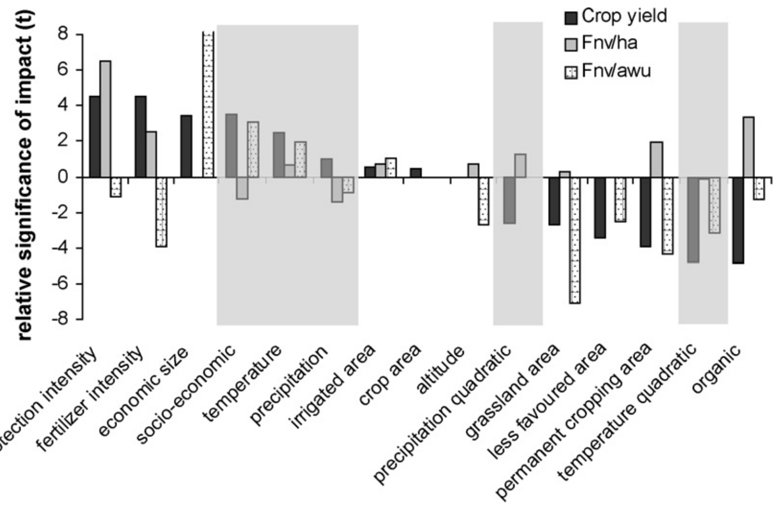

Fig. 3. Influence of farm characteristics, climatic conditions and socio-economic conditions (see Table 1 for description) on farm performance (spatial variability, farm level), measured by crop yield, fnv/ha and fnv/awu. Values are based on Reidsma et al. (2007). The relative significance of impact is based on the *t*-value, and the sign refers to positive or negative influence. Crop yield refers to the average *t*-value for soft wheat, grain maize, barley, potato and sugar beet yield. From left to right the variables are ranked from a highly positive significance to a highly negative significance impact on crop yields. The grey blocks indicate the variables measured at regional level; the others are at farm level.

from wheat yield variability at regional level and what this implied for climate impacts.

The diversity in farm type yield variability (SD), demonstrates the diversity in the responses of farm types in a region. This measure indicates per region the variation among farm types in their inter-annual wheat yield variability. SD was measured as the standard deviation in the relative yield anomaly per year of all farm types in a region, averaged over the study period (1990–2003) as

$$\mathrm{SD} = \sum_{t=1}^{N} \frac{\mathrm{sd}(Y_{A,1}, Y_{A,2}, \ldots, Y_{A,f})_t}{N} \quad \text{with}$$

$$Y_{A,i} = \frac{100 \times \left(y_{it} - \sum_{t=1}^{N} y_{it}/N \right)}{\sum_{t=1}^{N} y_{it}/N}$$

where sd is the standard deviation of relative yield anomalies ($Y_{A,i}$) of farm types i (i = 1, 2, . . ., f) per year t (t = 1, 2, . . ., N). Yield anomalies per farm type and year were calculated from the actual yield (y_{it}) related to the average of the study period. No trend was considered at farm type level as few trends were significant and trends can be distorted by missing years (Reidsma et al., 2009c). Relative yield anomalies were considered, as absolute yields differ per farm type within a region and therefore relative anomalies can be better compared than absolute anomalies.

A second measure, the regional farm diversity, demonstrated the diversity in the abundance of farm types. Farm diversity was based on the Shannon–Weaver index and expressed by intensity diversity, size diversity and land use diversity. Regional effects of inter-annual climate variability on wheat yields were measured by the Pearson correlation coefficient (r) between wheat yield anomalies from a linear trend and growing season temperature [r(*yield*,*temp*)]. Both diversity measures were related to r(*yield*,*temp*) in a regression model, in order to assess the relationship between farm diversity and regional effects of climate variability on crop productivity. For more details see Reidsma and Ewert (2008).

3.5. Comparison of potential and actual climate impacts

Projections on impacts of climate change on crop yields are generally based on crop models simulating impacts on potential or water limited yields. These impacts are considered as the potential impacts of climate change. Considering the IPCC definition of vulnerability (IPCC, 2001), the difference between the potential impacts as simulated by crop models and actual impacts based on observed data, can thus give some insights in the adaptive capacity.

We simulated potential and water limited yields of grain maize throughout the EU15 with the Crop Growth Monitoring System (CGMS), based on the WOFOST model, and compared these with actual maize yields (Reidsma et al., 2009b). Differences in spatial and temporal variability between simulated and actual maize yields were analysed using backward linear regression models in which climatic conditions and farm characteristics were included. Climatic conditions and farm characteristics can partly explain the deviation between potential and actual impacts of climate variability, and hence represent the influence of management and adaptation on climate impacts.

4. Results and discussion

4.1. Responses in crop yields and in farmer's income

The analysis of spatial variability in farm performance demonstrates that yields of most crops and labour productivity (fnv/awu) were higher in regions with a temperate climate and better socio-economic conditions (Fig. 3, grey blocks). Initially temperature had a positive impact, but the quadratic term had a very significant negative impact on both crop yields and fnv/awu. It can be argued that farms and regions that perform well are well adapted, which would confirm that Mediterranean regions have a lower adaptive capacity compared to northern European regions as suggested in Schröter et al. (2003). However, land productivity (fnv/ha) was not related to crop yields and was especially high in many Mediterranean regions with typically lower crop yields. Fig. 3 shows that the influence of many factors on fnv/ha was opposite to crop yields. This suggests that farmers in regions with relatively low crop yields get higher prices or grow more profitable crops to increase land productivity (whereas the smaller economic size explains the lower labour productivity).

One example of a more profitable crop is maize. In Fig. 4, we observe that while the influence of climatic conditions was significant for most other crops, for maize this was not the case (effects of temperature and precipitation were small; as models

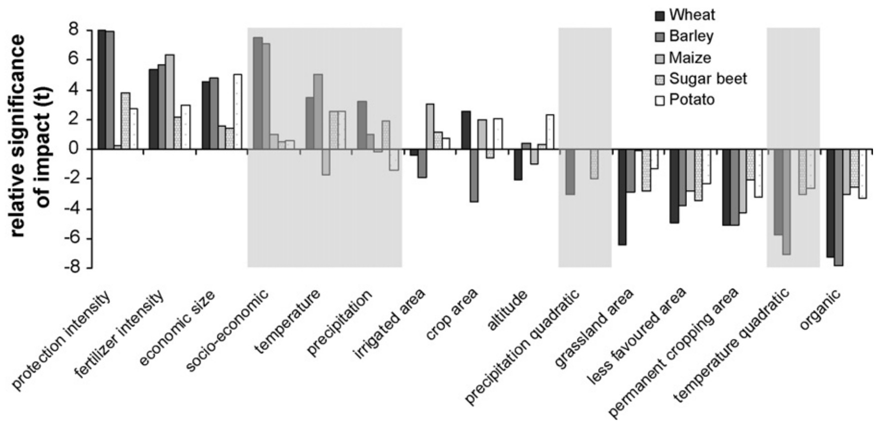

Fig. 4. Influence of farm characteristics, climatic conditions and socio-economic conditions (see Table 1 for description) on farm performance (spatial variability, farm level), measured by yields of soft wheat, grain maize, barley, potato and sugar beet (which were averaged in Fig. 3). Values are based on Reidsma et al. (2007). The relative significance of impact is based on the *t*-value, and the sign refers to positive or negative influence. From left to right the variables are ranked from a highly positive significance to a highly negative significance impact on average crop yields as in Fig. 3. The grey blocks indicate the variables measured at regional level; the others are at farm level.

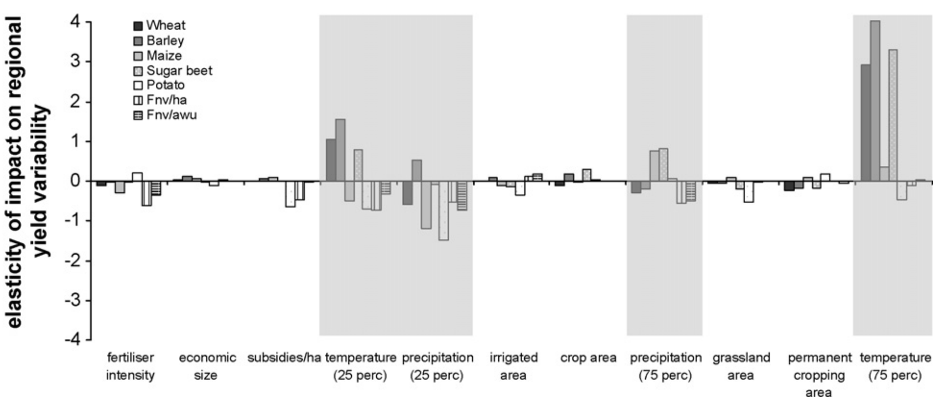

Fig. 5. Influence of farm characteristics and climatic conditions (see table 1 for description) on regional variability in farm performance from 1990 to 2003 (i.e., temporal variability, regional level), measured by yield of soft wheat, grain maize, barley, potato and sugar beet, and fnv/ha and fnv/awu. Values are based on Reidsma et al. (2009c). The impact is based on the elasticity at the mean of the variables. As climatic conditions have quadratic terms, elasticities are measured at the 25th and 75th percentile. From left to right the variables are ranked as for spatial variability in Fig. 3. In this analysis all variables are measured at regional level, but for comparison with other figures, climatic conditions are in grey blocks.

with quadratic terms did not perform better, these were not included). Also other factors like socio-economic conditions and economic size did not have a significant impact. This is likely due to the fact that crops that have relatively high potential yields (e.g. maize in Mediterranean regions) are managed better–resulting in high actual yields–than crops with low potential yields. In the context of adaptation, optimal management thus depends on what to optimize. If a crop (e.g. wheat) is not important, management will not concentrate on increasing its yields, but on other crops with potentially higher yields. As a result, the (spatial) effect of

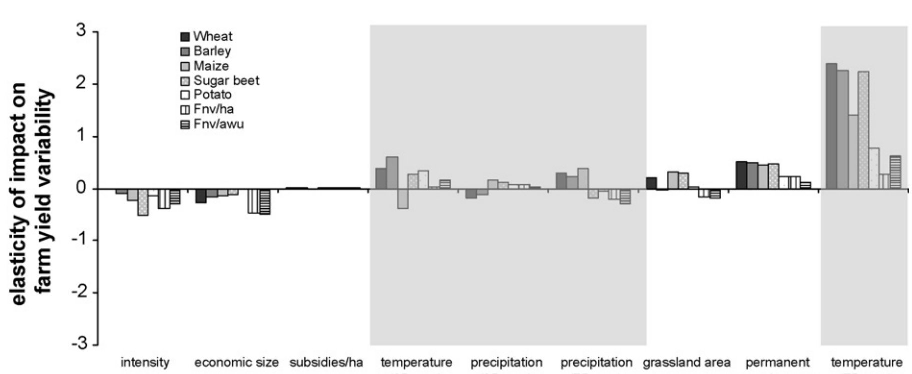

Fig. 6. Influence of farm characteristics and climatic conditions (see Table 1 for description) on farm level variability in farm performance from 1990 to 2003 (i.e., temporal variability, farm level), measured by yield of soft wheat, grain maize, barley, potato and sugar beet, and fnv/ha and fnv/awu. Values are based on Reidsma et al. (2009c). For the continuous variable subsidies/ha the impact is based on the elasticity at the mean; as climatic conditions have quadratic terms, elasticities are measured at the 25th and 75th percentile. The intensity, economic size, permanent cropping and grassland area refer to farm type dimensions, and the fixed effects referred to shifts between farm type dimensions. For comparison, elasticities were calculated by using values related to the farm type dimensions. From left to right the variables are ranked as for spatial variability in Fig. 3. The grey blocks indicate the variables measured at regional level; the others are at farm type level.

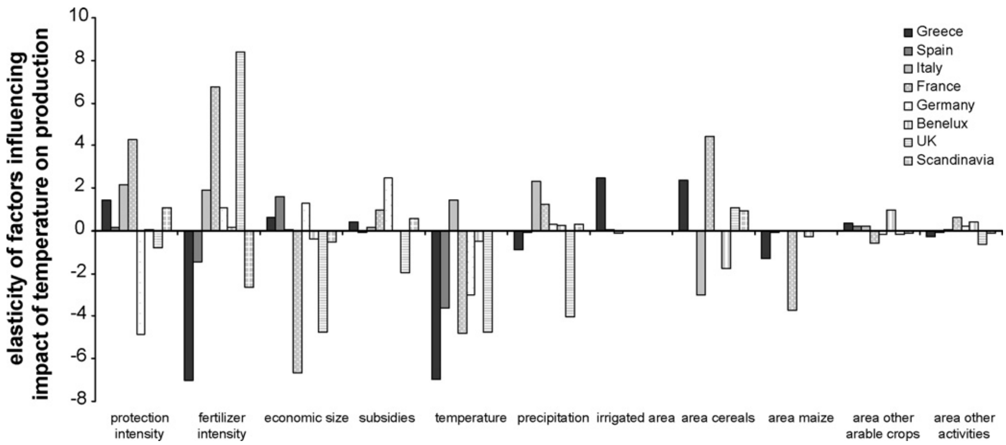

Fig. 7. Influence of farm characteristics, climatic conditions and socio-economic conditions (see Table 1 for description) on reducing or enhancing impacts of higher temperatures on production (temporal variability including interactions, regional level). The impact is based on the elasticity of the variables, production is measured by total output in euros (i.e., all crops and livestock). Values are based on Reidsma et al. (2009a). From left to right the variables are ranked as for spatial variability in Fig. 3.

climatic conditions were more pronounced for wheat compared to maize.

Clearly, farm performance also differed per farm within a region and this was largely dependent on three farm characteristics: intensity, farm size and land use (Reidsma et al., 2007). Although variable per crop as mentioned above, in general crop yields increased with increasing farm intensity (i.e., fertilizer use, crop protection use, irrigated area, non-organic), farm size (i.e., economic size) and arable land use (i.e., grassland and permanent cropping area had a negative impact). However, differences were observed between yields of different crops and farmers' income per hectare or per working unit, so that vulnerability and adaptive capacity will differ among indicators.

4.2. Responses to spatial and to temporal climate variability

Regions that obtained higher crop yields had smaller (relative) variability herein. At higher temperatures, crop yields were lower (Figs. 3 and 4) and regional crop yield variability was higher (Fig. 5). However, when analyzing yield variability at farm level (Fig. 6), we observed that the influence of climatic conditions appeared smaller than when assessed at regional level. At regional level, the impact of farm characteristics was heterogeneous, while at farm level impacts were larger, significant and coherent among crops. Farm characteristics are thus important.

When analyzing the interaction between farm characteristics and temperature, i.e., the adaptive capacity, it appeared that the influence of farm characteristics on climate impacts, largely differed per region (Fig. 7). For example, in France and the UK, a large economic size enhanced negative effects of higher temperatures; in other regions the influence was small. Other analyses on relationships between crop yield variability and climate variability showed that in northern European regions higher temperatures generally had a more negative impact on wheat yields (Fig. 8) and maize yields (Reidsma et al., 2009b) compared to Mediterranean regions. Interestingly, this implies that farms and regions that perform well and seem better adapted to prevailing conditions do not adapt better to climate variability and climate change.

Although studying a different environment, Bharwani et al. (2005) drew similar conclusions related to farm types in Lesotho. Poor farmers adapted better to climate variability than richer farmers who respond mainly to market signals. For richer farmers, this lead to better average farm performance, but larger decreases in bad years. As richer farmers have only few strategies, they are more cautious and only change if they trust the forecasts. Hence, they are more vulnerable to extreme climatic conditions.

Also van der Dries (2002) showed that small-scale traditional farms can better cope with climate variability than modern intensive farms. Nevertheless, smaller farms may have a higher capacity to adapt in France, but a lower capacity to adapt in Spain (Fig. 7). Also farmer's objectives and perceptions, influencing awareness, play an important role. Results suggest that at regional level a higher exposure to extreme climatic conditions stimulates adaptation (e.g. Fig. 8). As farms are generally adapted to prevailing conditions, farms in less favourable areas are not necessarily more vulnerable than farms in favourable areas. This was also concluded for Australian (Nelson et al., 2005) and African agriculture (Challinor et al., 2007).

A similar conclusion can be obtained when analysing trends from 1990 to 2003 (Fig. 9). Although since 1960 crop yields have increased much faster in temperate regions compared to warmer regions (Ewert et al., 2005), in the last decades also relatively high trends were observed in Mediterranean regions, where temperatures are generally higher (Reidsma et al., 2009c). Yields of most crops are still relatively low in Mediterranean regions, but from 1990 to 2003 also fnv/ha and fnv/awu increased faster compared

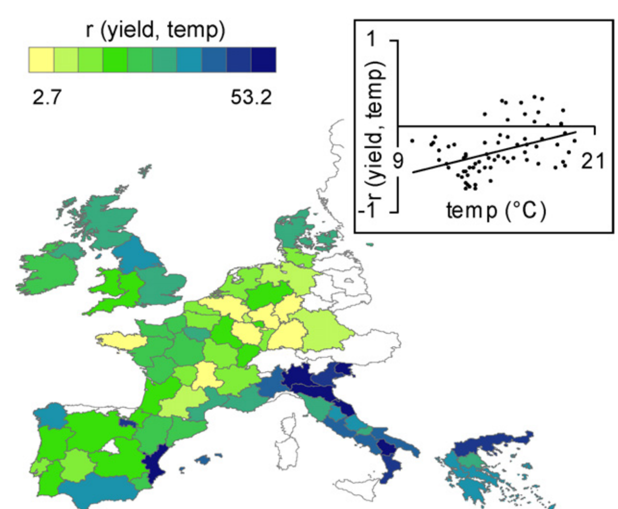

Fig. 8. Spatial distribution of the correlation between inter-annual variability in temperature and wheat yield anomalies [*r*(*yield*,*temp*)], and relationships to average temperature (*temp*, °C) from 1990 to 2003. Based on the relationship for spatial variability (Fig. 3) a negative relationship for temporal variability can be expected; this is the case in many temperate regions, but the relationships are often positive in warmer regions. *Source*: Reidsma and Ewert (2008).

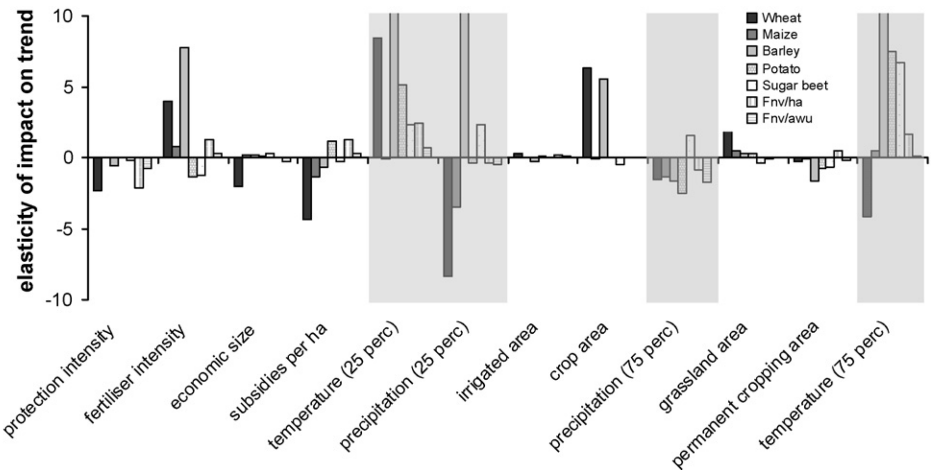

Fig. 9. Influence of farm characteristics, climatic conditions and socio-economic conditions (see Table 1 for description) on trends in regional farm performance from 1990 to 2003 (i.e., temporal trends, regional level), measured by yield of soft wheat, grain maize, barley, potato and sugar beet, and fnv/ha and fnv/awu. Values are based on Reidsma et al. (2009c). The impact is based on the elasticity at the mean of the variables. As climatic conditions have quadratic terms, elasticities are measured at the 25th and 75th percentile. From left to right the variables are ranked as for spatial variability in Fig. 3. In this analysis all variables are measured at regional level, but for comparison with other figures, climatic conditions are in grey blocks.

to temperate regions. This suggests that farmers in regions with low crop yields adapt by decreasing input costs, diverting to other crops or increasing subsidized activities (as fnv approximates outputs − inputs + subsidies − taxes), but also by using new practices to increase yields. Higher product quality or increased market value due to scarcity may also have led to higher output prices (which are observed in the FADN data).

4.3. Responses at farm and at regional level

As observed in Section 4.2, efficient adaptation strategies differed largely per region and per farm and were not only dependent on changes in climatic conditions, but also largely on current management. Figs. 5 and 6 showed that while at regional level yield and income variability seem largely dependent on climatic conditions, the analysis at farm type shows that farm characteristics become more important at lower levels.

In Fig. 10 we observe that at the regional level an important adaptation was the diversification among farm types. Regressing the farm type yield variability (SD) against the Pearson correlation coefficient between wheat yield anomalies and temperature (i.e., *r*(*yield*,*temp*)) (Fig. 8), revealed that a larger number of farm types with different strategies to adapt, resulted in smaller impacts of climate variability at the regional level ($p = 0.04$). Another regression model including farm diversity measures, showed that the diversity in farm size and intensity, particularly high in Mediterranean regions, reduced vulnerability of regional wheat yields to climate variability (Reidsma and Ewert, 2008).

As not many studies have been looking at regional diversity, it would be interesting to further explore how regional farm diversity is related to management diversity. The studies of Di Falco and Chavas (2008) and di Falco et al. (2008) suggest that part of the management diversity can be explained by regional crop cultivar diversity. Like farm diversity, this was specifically high in south-

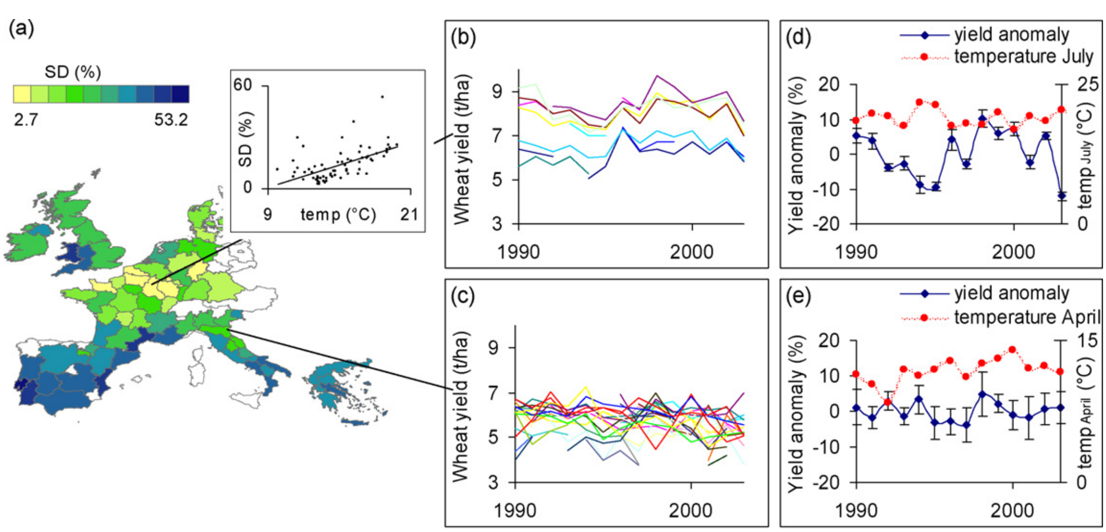

Fig. 10. (a) Spatial distribution of the diversity in farm type yield variability (SD, %), and relationships to average temperature (*temp*, °C) from 1990 to 2003. Wheat yield variability is similar for different farm types in (b) Champagne-Ardenne, while in (c) Emilia-Romagna the diversity in wheat yield variability is larger. In (d) Champagne-Ardenne standard deviations in the relative wheat yield anomaly for individual years are small (SD = 3.7) and regional yield anomalies (from the trend) are significantly different from zero and correlated to temperature ($r = -0.66$ with *tempJuly*, $r = -0.44$ with *temp*). However, in (e) Emilia-Romagna the standard deviations are large (SD = 8.3) and regional yield anomalies are not significantly different from zero and are not significantly correlated to temperature ($r = -0.13$ with *tempApril*, $r = 0.33$ with *temp*). Note, temperatures shown in (d) and (e) refer to the months with the largest negative correlation (*Source*: Reidsma and Ewert, 2008).

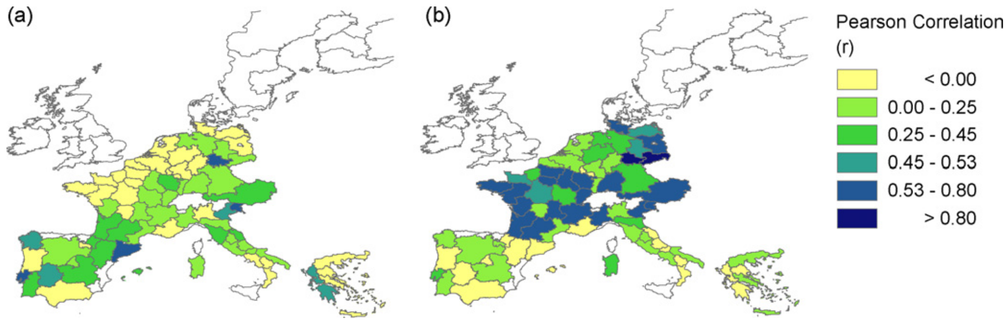

Fig. 11. The correlations between temporal variability in actual and simulated yields per HARM region with (a) actual yield and potential yield and (b) actual yield and water limited yield. An $r > 0.45$ corresponds to $p < 0.10$; $r > 0.53$ corresponds to $p < 0.05$ (Source: Reidsma et al., 2009b).

ern Italian regions and reduced vulnerability to climatic variability. The lower vulnerability in Mediterranean regions suggests that a higher exposure to extreme conditions stimulates adaptation. Local studies in Mediterranean regions (Orlandini et al., 2008; Utset et al., 2008), but also in temperate regions as in the Netherlands (Grontmij, 2009) confirm this. Nevertheless, at farm level, some farm types may be vulnerable.

Due to the large variety of farms, not only in size, intensity and land use, but also in objectives and perspectives, adaptation strategies are difficult to generalize at farm (type) level. Fig. 7 showed for example that fertilizer intensive farmers can largely reduce the negative effects of higher temperatures in the UK, France and Italy, while in other regions, the effect is small or even negative. Reducing the maize area when temperatures increase seems to be a good adaptation strategy in France, but in other regions in the EU15 this strategy has little effect on total outputs. Clearly, the specific adaptation response does not only depend on the changes in potential or water limited maize yields, but on many other factors influencing actual yields.

4.4. Potential and actual climate impacts

The analysis comparing spatial yield variability in simulated and actual maize yields showed that higher temperatures tend to increase actual yields compared to potential yields. In Fig. 4 we observed that climate impacts were not significant for actual maize yields, but this differed for potential yields (not shown here; see Reidsma et al., 2009b). Also the temporal analysis of yield variability indicated that in Mediterranean regions higher temperatures had a more positive impact on actual yields than on the simulated potential yields. The opposite was the case for temperate regions. Fig. 11 shows that there was a large difference between how potential and/or water limited yields respond to climatic variability compared to how actual yields respond to climatic variability. In southern Europe, most maize crops are irrigated, while in northern Europe maize this is generally not the case. Hence, in southern Europe, relationships with potential yields were expected, while in northern Europe, relationships with water limited yields were expected. The fact that no relationships were found in most Mediterranean regions, suggests that farmers in Mediterranean regions have adapted to higher temperatures by, for example, growing more heat resistant cultivars, an adaptation strategy not considered in the crop model.

Farm characteristics explained some of the differences between simulated and actual yields. Unsatisfactory simulations in spatial yield variability (based on CGMS) were partly explained by the proportion of the maize area in the total arable area, farmers' income and irrigated area (similar to Fig. 4). Improving estimations of temporal variability in actual maize yields requires regional specific models that, besides improving cultivar coefficients, relate to the farm characteristics important in the region.

As management differs per region, farm type and year, modelling regional impacts of climate change and variability based on mechanistic crop models is only sufficient if the variety of management activities in a region is captured adequately. However, representative input parameters are difficult to obtain and to project for the future, which highlights the need for simplified approaches to represent management activities in a region (Oomen et al., 2009). Farm characteristics provide some link to management and including them in a regional crop model can improve the simulation of climate variability impacts and hence yield projections.

As farmers adapt their practices to prevailing conditions, 'potential impacts' as simulated by crop models that consider only potential and/or water limited yields do not exist in practice. Nevertheless, most studies referred to in the latest IPCC report (Easterling et al., 2007) still base projections on these type of 'potential impacts'. Clearly, simulations of potential impacts will need to be extended by considering management to project actual yields.

An approach that comes close to this was presented by Ewert et al. (2005), who linked actual yields from agricultural statistics to agro-environmental zones (Metzger et al., 2005). By assessing shifts in agro-environmental zones, potential impacts on actual crop yields could be evaluated. Nevertheless, as many changes affect farmers, these potential impacts should also be placed into context. The impact of technological development on the increase in crop yields has been very high since the 1960s and it is likely that this will also be the case in the coming decades (Ewert et al., 2005). Technological development influences both potential yields (e.g. new cultivars) and actual yields (e.g. improvements in fertilizer management) and will likely influence adaptation to climate change. As technology is continuously improving, 'potential impacts' are not explicitly quantifiable, leaving it as mainly a theoretical concept.

4.5. Agricultural adaptation

Although agriculture will adapt, this does not imply that all adaptations will be autonomous. Technological development is based on awareness of where improvements are needed. The increasing awareness that climate change is happening will likely positively influence adaptation to climate change. Nevertheless, stimulation by policy makers is needed to create an environment in which farmers can adapt. Planned adaptation is needed to be able to prepare for future changes. The fact that adaptation can reduce climate change impacts is not a reason to be less cautious, but an incentive to develop efficient adaptation strategies and reduce vulnerability.

To assess the effectiveness of adaptation strategies, frameworks should not start from the modelling perspective, but from the stakeholders perspective: (1) assess current vulnerability to climatic variability (including aspects that cannot be simulated with quantitative models), (2), assess climate risks (considering climate scenarios), and (3) develop adaptation strategies (based on integrated assessments and stakeholder involvement), either relevant at farming system level or at policy level (Burton and Lim, 2005).

Simulations of potential and water limited crop yields which ignore the importance of farm type and related management effects fail to reproduce the practical situation at farm and regional level. Information on farm characteristics and management can be obtained from other models (e.g. economic and land use models) but requires adequate linking. Although mechanistic modelling of all processes determining crop yield and agricultural performance is not feasible, for reliable projections of the impacts of climate change on agriculture, models are needed that represent the actual situation and adaptation processes more accurately.

This study identified factors that influence adaptation and hence reduce vulnerability. The importance of these factors may change however when thresholds are approached. For example, although irrigated agriculture in Spain is currently not vulnerable, it may become so when water availability is decreasing and competition for water resources increases. Also for this reason, a linking of models is needed to simulate feedbacks. This may be accomplished in integrated modelling frameworks such as IMAGE (MNP, 2006) and SEAMLESS-IF (van Ittersum et al., 2008). Resilience theory (Gunderson and Holling, 2002) further provides a basis to assess vulnerability of systems when thresholds play a role (Bennett et al., 2005; Reidsma, 2007).

5. Concluding remarks

This study analysed the adaptation of farmers and regions in the European Union to prevailing climatic conditions, climate change and climate variability in the last decades (1990–2003) in the context of other conditions and changes. We compared (1) responses in crop yields with responses in farmers' income, (2) responses to spatial climate variability with responses to temporal climate variability, (3) farm level responses with regional level responses and (4) potential climate impacts (based on crop models) with actual climate impacts (based on farm accountancy data).

We conclude that impacts on crop yields cannot directly be translated to impacts on farmers' income, as farmers adapt by changing crop rotations and inputs, and incomes are largely influenced by subsidies. Secondly, the impacts of climatic conditions on spatial variability in crop yields and farmers' income, with generally lower yields in warmer climates, are different from the impacts of temporal variability in climate, where more heterogeneous patterns are observed across regions in Europe. Thirdly, actual impacts of climate change and variability are largely dependent on farm characteristics (e.g. intensity, size, land use), which influence management and adaptation. To accurately understand impacts and adaptation, assessments should consider responses at different levels or organization. As different farm types adapt differently, a larger diversity in farm types reduces impacts of climate variability at regional level, but certain farm types may still be vulnerable. Lastly, we observed that management and adaptation can largely reduce the potential impacts of climate change and climate variability on crop yields and farmers' income. Farmers continuously adapt to changes, which affects the current situation as well as future impacts. The separation of potential impacts and adaptive capacity is theoretically a useful concept, but cannot be quantified for practical situations. Therefore, for reliable projections of the impacts of climate change on agriculture, adaptation should not be seen anymore as a last step in a vulnerability assessment; rather it has to be an integrated part of the models used to simulate crop yields, farmers' income and other indicators related to agricultural performance.

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