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Climate impacts on European agriculture and water management in the context of adaptation and mitigation—The importance of an integrated approach

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A B S T R A C T

We review and qualitatively assess the importance of interactions and feedbacks in assessing climate change impacts on water and agriculture in Europe. We focus particularly on the impact of future hydrological changes on agricultural greenhouse gas (GHG) mitigation and adaptation options. Future projected trends in European agriculture include northward movement of crop suitability zones and increasing crop productivity in Northern Europe, but declining productivity and suitability in Southern Europe. This may be accompanied by a widening of water resource differences between the North and South, and an increase in extreme rainfall events and droughts. Changes in future hydrology and water management practices will influence agricultural adaptation measures and alter the effectiveness of agricultural mitigation strategies. These interactions are often highly complex and influenced by a number of factors which are themselves influenced by climate. Mainly positive impacts may be anticipated for Northern Europe, where agricultural adaptation may be shaped by reduced vulnerability of production, increased water supply and reduced water demand. However, increasing flood hazards may present challenges for agriculture, and summer irrigation shortages may result from earlier spring runoff peaks in some regions. Conversely, the need for effective adaptation will be greatest in Southern Europe as a result of increased production vulnerability, reduced water supply and increased demands for irrigation. Increasing flood and drought risks will further contribute to the need for robust management practices.

The impacts of future hydrological changes on agricultural mitigation in Europe will depend on the balance between changes in productivity and rates of decomposition and GHG emission, both of which depend on climatic, land and management factors. Small increases in European soil organic carbon (SOC) stocks per unit land area are anticipated considering changes in climate, management and land use, although an overall reduction in the total stock may result from a smaller agricultural land area. Adaptation in the water sector could potentially provide additional benefits to agricultural production such as reduced flood risk and increased drought resilience.

The two main sources of uncertainty in climate impacts on European agriculture and water management are projections of future climate and their resulting impacts on water and agriculture. Since changes in climate, agricultural ecosystems and hydrometeorology depend on complex interactions between the atmosphere, biosphere and hydrological cycle there is a need for more integrated approaches to climate impacts assessments. Methods for assessing options which "moderate" the impact of agriculture in the wider sense will also need to consider cross-sectoral impacts and socio-economic aspects.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC)'s Working Group 1 report (IPCC, 2007a) reinforced a scientific consensus that man-made greenhouse gas emissions are likely to have made a significant contribution to recent changes in climate, and on further projected changes in global climate in the coming decades. In addition to this, the residual effect of past greenhouse gas emissions on future global climate means there is a commitment to climate change until about 2030–2040, regardless of emissions scenario (IPCC, 2007a). This implies that society will need to adapt to these committed changes in climate during this period. Climate change is likely to have wide-ranging impacts on both the water and agricultural sectors (IPCC, 2007b) in many regions of the world.

This has increased the need for robust information on how climate change could affect different sectors including agriculture and water. In particular there is a need for better information to support adaptation planning over the next few decades since this is an appropriate time horizon for considering and implementing practical and policy options to deal with climate change.

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While the need for effective adaptation options in agriculture is recognised, the sector also has considerable potential as a short-to-mid term climate mitigation option (Soussana et al., 2004; Smith et al., 2007, 2008; Schlamadinger et al., 2007). There are many uncertainties regarding climate impacts on water and agriculture including the many complex interactions between the two sectors and the changing climate.

Changing the use and management of agricultural land to support mitigation objectives, or adaptation plans is likely to have other environmental (Freibauer et al., 2004) and climatic effects including those on hydrology, which may be beneficial or detrimental to the original objective. Changing water management practices to adapt to climate change could also potentially affect the effectiveness of agricultural mitigation and adaptation options. For instance, as well as increasing agro-ecosystem carbon storage, improved field boundary management could create buffer zones to prevent nutrient losses to surface water (Falloon et al., 2004) and reduce surface runoff and erosion. Similarly planting biofuel crops on arable lands could act as a significant carbon mitigation option, but while they could also reduce nitrate losses (Powlson et al., 2001) and soil erosion (Berndes and Börjesson, 2002; Berndes et al., 2004; Börjesson and Berndes, 2006), opposite effects such as intensified water use and increased nutrient losses (Unkovich, 2003; Dias de Oliviera et al., 2005; IPCC, 2008) could result if poorly located, designed and managed.

Soil organic matter (SOM) is composed of approximately 45% soil organic carbon (SOC). Increasing SOM (and thus SOC) in agricultural soils to meet mitigation objectives will also improve their water holding capacity (Huntington, 2006), potentially reducing crop system water losses and the need for irrigation. Soil moisture can also alter albedo (Post et al., 2000). For limited geographic areas and soils with similar morphologic properties, SOM content can also affect soil colour and albedo (Alexander, 1969; Fernandez et al., 1988; Schulze et al., 1993). Changes in soil moisture and SOM status could therefore also affect the local radiative balance and potentially cause additional local cooling or warming, which in turn would impact evaporation rates from soil.

On the other hand, since SOC losses could increase with rising temperatures (Jenkinson et al., 1991; Cox et al., 2000; Jones et al., 2005; Friedlingstein et al., 2006; Falloon et al., 2006a), the changing climate could alter the potential for mitigation in the agriculture sector (Falloon et al., 2009a). Climate-induced reductions in SOC content could also alter the effectiveness of adaptation options in agriculture by changing soil fertility, nutrient status, tilth and water holding capacity (Falloon et al., 1998). The projected trend towards hotter and drier summers (IPCC, 2007a) and increased droughts (Lehner et al., 2006) in Europe may lead to increased crop irrigation needs. This would affect water availability for other sectors (Betts, 2005), but also alter agricultural SOC storage since moisture is a strong driver of SOC changes (Falloon et al., 2009b). For this reason, increasing irrigation of croplands would also likely reduce SOC storage, assuming net primary productivity (NPP) remained unchanged. However, on balance there is a general concensus that irrigation leads to an overall increase in SOC (Follett, 2001; Lal, 2004) when NPP changes are considered. Such interactions are numerous, complex and non-linear (Falloon and Smith, 2003; Betts, 2005; Falloon et al., 2009a), and often poorly-understood.

Our aim is to review and qualitatively assess the importance of interactions and feedbacks in assessing climate change impacts on water and agriculture in Europe. Since there are several recent reviews of climate-crop modelling (Betts, 2005; Hansen et al., 2006), ecosystem–hydrology–climate interactions (Betts, 2006), diffuse pollutant mobilisation (MacLeod et al., 2009-this issue) and agricultural contaminant fate (Boxall et al., 2009), we do not focus on these aspects in detail. Here, we focus particularly on the impact of future hydrological changes on agricultural mitigation and adaptation options (Fig. 1). Our approach is to:

a) review the main direct projected impacts of climate change on agriculture and water
b) assess how future hydrological changes might affect adaptation and mitigation in agriculture
c) assess the complex nature of interactions and feedbacks between agriculture and water in a changing climate in a broader sense
d) assess major sources of uncertainty and research gaps.

While our study focuses on Europe in general, we make reference to studies from other regions of the world where appropriate.

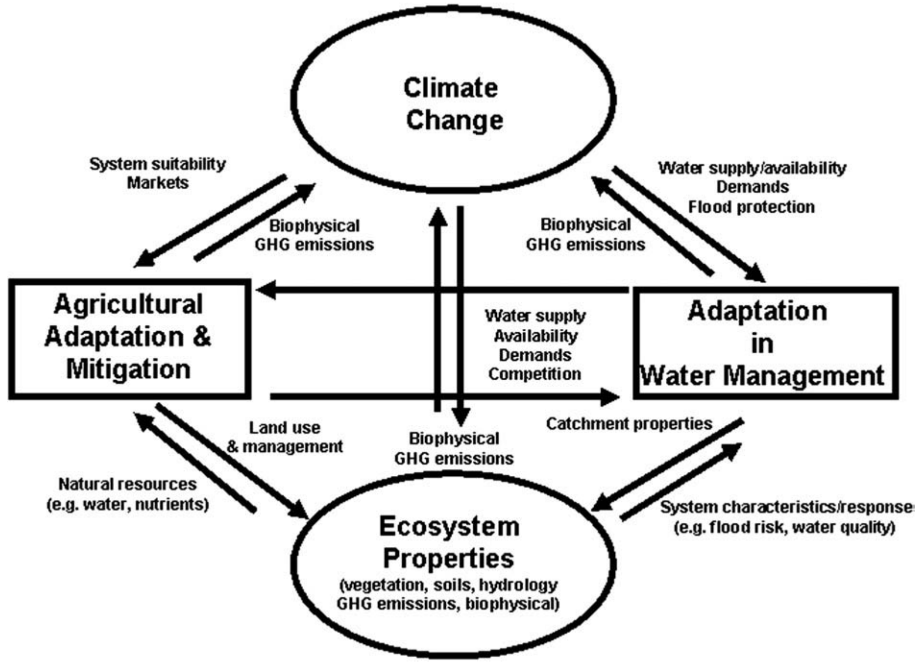

Fig. 1. Interactions between climate change, adaptation/mitigation in agriculture, adaptation in water management and ecosystem properties.

2. Impacts of climate change on water and agriculture in Europe

2.1. Projected changes in European climate

IPCC (2007a) projected significant warming over Europe by the 2030s, with greater warming in winter in the North, and in summer in Southern and Central Europe. Mean annual precipitation is projected to increase in Northern Europe and decrease in the south (Maracchi et al., 2005). Significant changes to climate variability and extremes are also projected, although many of the studies below refer to the 2050s or 2080s.

Increased inter-annual and daily temperature variability in summer are projected by General Circulation Model (GCM) and Regional Climate Model (RCM) simulations particularly for southern and central parts of Europe and mid-latitude Western Russia (IPCC, 2007a, and references therein). Conversely, temperature variability is projected to decrease in most of Europe in winter, both on inter-annual and daily time scales, especially in eastern, central and northern Europe (IPCC, 2007a and references therein). Heat wave frequency, intensity and duration are also generally expected to increase, while the number of frost days is likely to decrease (IPCC, 2007a).

An increase in the magnitude and frequency of high precipitation extremes is likely for northern Europe, and in central and Southern Europe in winter, based on several GCM and RCM studies (for examples, see IPCC, 2007a). There is general agreement on projected increases in summer extreme daily precipitation from GCM and RCM projections (IPCC, 2007a), particularly in central, Southern and Mediterranean Europe despite the decrease in both mean precipitation and the number of wet days (Frei et al., 2006).

Longer, more frequent droughts could occur in Southern, Central and Eastern Europe and the Mediterranean (IPCC, 2007a). There is also some consensus on projected decreases in cyclone numbers in the Mediterranean Sea (IPCC, 2007a). Rises in sea level may lead to loss of farmland, particularly in low-lying areas such as the Netherlands (IPCC, 2007b) by inundation and increasing salinity of soils and groundwater (Motha, 2007).

These changes in climate are likely to have significant impacts on both the agricultural and water sectors over the next few decades (IPCC, 2007b).

2.2. Impacts of climate change on European agriculture

Small overall increases in crop productivity are anticipated in Europe as a result of climate change and increased atmospheric carbon dioxide (CO_2). However, technological development could outweigh these effects (Ewert et al., 2005) resulting in combined wheat yield increases of 37–101% by the 2050s, dependent on scenario (Ewert et al., 2005). Coupled with decreasing or stabilising food and fibre demand, these yield increases could lead to a decrease in total agricultural land area in Europe (Fig. 2: Rounsevell et al., 2005; Schröter et al., 2005).

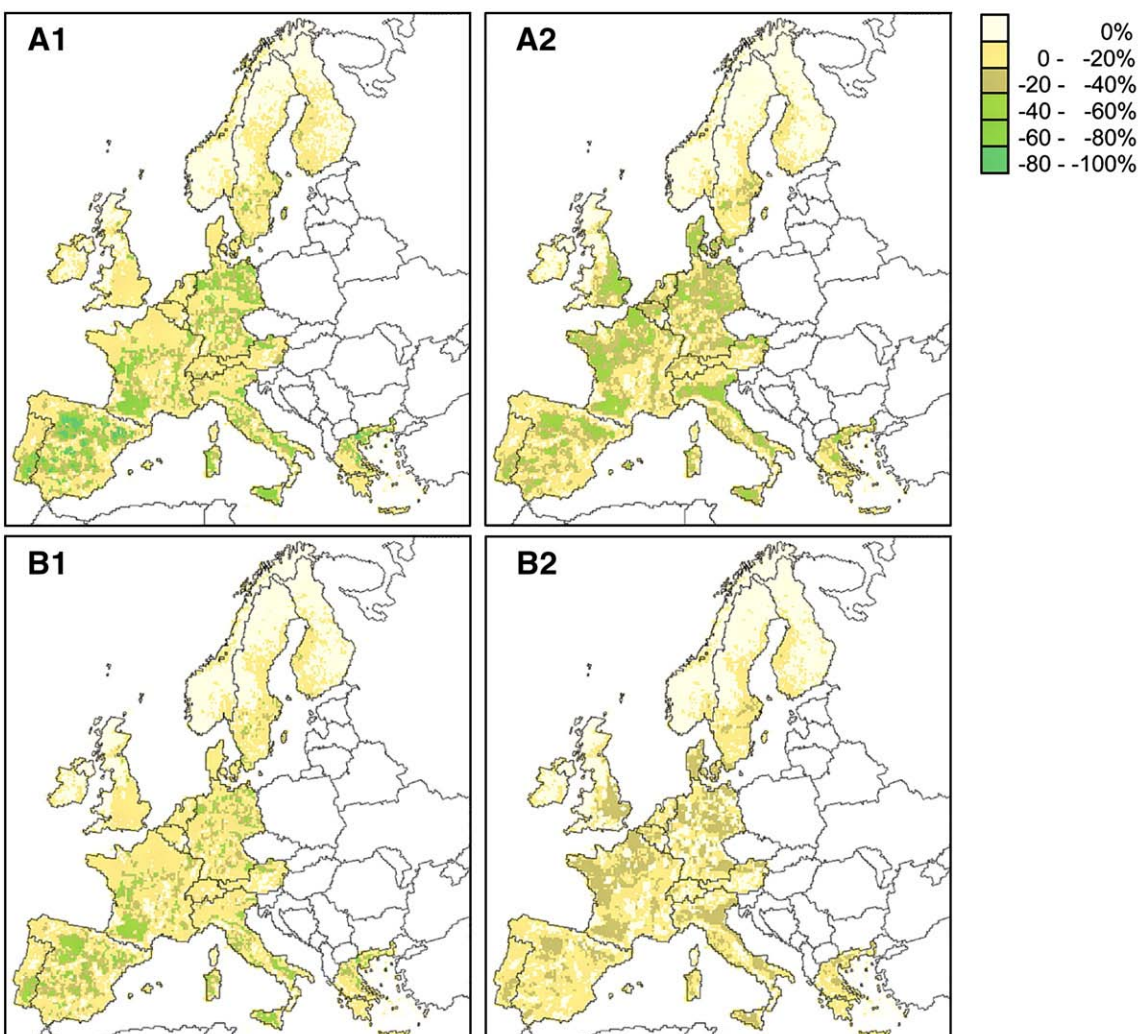

Fig. 2. Change in cropland area (for food production) by 2080 compared with the baseline (percentage of EU15 + area) for the four IPCC SRES storylines A1(F1), A2, B1 and B2 with climate projected by HadCM3. From Schröter et al. (2005). Reprinted with permission from AAAS.

Table 1
Main projected hydrological changes for Europe and their implications for adaptation and mitigation in agriculture.

Projected hydrological changes		Implications of hydrological changes for adaptation measures in agriculture	Vulnerability of agricultural mitigation measures to hydrological changes
Widening of water resource differences between Northern and Southern Europe	Increased water supply from precipitation in Northern Europe	Reduced vulnerability of production Reduced water demand for irrigation Where an excess occurs—direct negative impacts (soil properties, damage to plant growth); indirect impacts (harming/delaying farming operations)	Increased NPP, C inputs and above ground carbon storage (Excess precipitation may reduce productivity) Increased soil carbon decomposition and GHG fluxes
	Reduced water supply from precipitation in Central and East Mediterranean Europe	Increased vulnerability of production Increased water demand for irrigation	Reduced NPP, C inputs and above ground carbon storage Reduced soil carbon decomposition and GHG fluxes Increased soil carbon losses via wind erosion
Changes in annual average runoff	Increases in North/North west Europe	Reduced vulnerability of production Increased extractable water supply for irrigation and other purposes (e.g. livestock)	Improved water availability may enhance NPP, C inputs and above ground carbon storage Irrigation may increase soil C decomposition and GHG fluxes
	Decreases in South/South east Europe	Increased vulnerability of production Reduced extractable water supply for irrigation and other purposes (e.g. livestock)	Reduced water availability may limit NPP, C inputs and above ground carbon storage Reduced irrigation may limit soil C decomposition and GHG fluxes
Reduced groundwater recharge in central and Eastern Europe		Reduced extractable water supply for irrigation and other purposes (e.g. livestock) May lead to soil salinisation in marginal areas	Reduced water availability may limit NPP, C inputs and above ground carbon storage Soil C decomposition and GHG fluxes may be limited in drier soils Salinisation may reduce NPP, C inputs to soil and above ground carbon storage and negatively affect soil biota
Drier soils (particularly in summer and Continental Europe) due to increased evapotranspiration		Increased water demand for irrigation Increased wind erosion (May be offset by impact of elevated CO_2)	Reduced soil moisture may limit NPP, C inputs and above ground carbon storage Soil C decomposition and GHG fluxes may be limited in drier soils Erosion may increase soil C losses
Changes in seasonal river flow patterns	Earlier spring runoff peaks in the North.	Water may not be usable if increases occur during peak period Potential summer irrigation shortages	Increased erosion and soil carbon loss may occur if runoff peaks coincide with waterlogged conditions Increased N_2O emissions may occur during earlier spring thaw Summer irrigation shortages may limit NPP, C inputs and above ground carbon storage and reduce soil C decomposition and GHG fluxes
	Higher winter flows and lower summer flows in the Rhine, Slovakian rivers, the Volga and central and eastern Europe.	Winter increases may not be useable (quality and quantity) Summer irrigation shortages	Increased erosion and soil carbon loss may occur if runoff peaks coincide with winter waterlogged conditions Summer irrigation shortages may limit NPP, C inputs and above ground carbon storage and reduce soil C decomposition and GHG fluxes

	Significant decreases in summer flows in central and Southern Europe.	Summer irrigation shortages	Summer irrigation shortages may limit NPP, C inputs and above ground carbon storage and reduce soil C decomposition and GHG fluxes
	Initial increases in summer flows in the Alps but significant long-term reductions	Initial improvement in water supply for irrigation; long-term reduction	Initial improved water supply may enhance NPP, C inputs and above ground carbon storage, but increase soil C decomposition Long-term water shortages may limit NPP, C inputs and above ground carbon storage and reduce soil C decomposition and GHG fluxes
Longer, more frequent droughts especially in Southern, Central and Eastern Europe and the Mediterranean.		Land degradation and wind erosion Reduced yields, increased crop stress, damage and failure Increased yield variability Increased livestock deaths Increased wildfire occurrence Some positive impacts—pest reduction, snow removal and introduction of long-term water conservation measures	Combination of threats may limit NPP, C inputs and above ground carbon storage and extreme drying may reduce soil C decomposition and GHG fluxes – potential overall ecosystem C release and soil C loss
Increased risk of flood hazards across most of North, Central and Eastern Europe and an increased risk of flash flooding and heavy precipitation events for much of the region		Damage to crops and plant growth Increased yield variability Direct negative impacts on soil properties (water-logging, erosion, nutrient loss) Indirect impacts such as harming (soil compaction) or delaying farming operations In arid regions, heavy precipitation may increase salinisation due to increased water loss past crop root zone Some positive impacts—where additional water can be harnessed, or where flood deposits replenish nutrients; may prevent damaging freezes	Combination of threats may limit NPP, C inputs and above ground carbon storage, extreme wetness may reduce soil C decomposition Increased erosion may increase soil C losses Salinisation may reduce NPP, C inputs to soil and above ground carbon storage and negatively affect soil biota
Significant increases in irrigation water demands, particularly for Central, Eastern and Mediterranean Europe, substantial demands occurring where they are currently very small (e.g. Ireland).		Increased need for drought tolerant crop and livestock systems	Drought tolerant crop and livestock systems will increase resilience, but potentially increase overall GHG emissions (e.g. irrigation, summer housing) Overall potential soil C gains from increased irrigation
Increased competition for water and water stress particularly in Central and Southern Europe, especially in summer.		Likely increased water prices and more stringent abstraction controls Increased need for water efficiency and conservation measures	Better water efficiency and conservation will increase resilience

After IPCC (2007b,c) and IPCC (2008).

Decreases in total agricultural land area are projected under all the IPCC Special Report on Emissions Scenarios (SRES) storylines (IPCC SRES, 2000), but are most marked in Southern Europe. However, increases in productivity may not necessarily lead to overall increases in carbon storage since climate change could also increase the length of the season when respiration occurs (Harrison et al., 2008). Air pollution could also reduce crop yields since tropospheric ozone has negative effects on biomass productivity (Booker and Fiscus, 2005; Liu et al., 2005; Sitch et al., 2007).

In Northern Europe, the suitability and productivity of crops is likely to increase and extend northwards, especially for cereals and cool season seed crops (Maracchi et al., 2005; Tuck et al., 2006; Olesen et al., 2007). Crops now prevalent mostly in Southern Europe such as maize, sunflower and soybeans could also become viable further north and at higher altitudes (Hilden et al., 2005; Audsley et al., 2006; Olesen et al., 2007). Here, yields could increase by as much as 30% by the 2050s, dependent on crop (Alexandrov et al., 2002; Ewert et al., 2005; Richter and Semenov, 2005; Audsley et al., 2006; Olesen et al., 2007). In Central and Eastern Europe, climate change and technological advances will likely increase productivity, leading to replacement of fodder crops with cash crops (Henseler et al., 2008).

The area of grasslands in Europe is also likely to decrease by the end of this century (Rounsevell et al., 2006). Although warming alone could reduce grass yields (Gielen et al., 2005; de Boeck et al., 2006), grassland productivity in Northern Europe is likely to increase overall (Byrne and Jones, 2002; Kammann et al., 2005). In Central and Eastern Europe, intensive grasslands may be replaced by more extensive pastures (Henseler et al., 2008).

The annual temperature increases may lead to a longer crop (and grass) growing season and vegetative growth and cover, particularly in Northern Europe (MAFF, 2000; Christidis et al., 2007; Semenov, 2008). Negative impacts in Northern Europe could include increased pest and disease pressures and nutrient leaching, and reduced SOM content (Maracchi et al., 2005).

Conversely, crop productivity and suitability are likely to decrease where precipitation decreases significantly such as the Mediterranean, Southern and South-eastern Europe (Olesen and Bindi, 2002; Maracchi et al., 2005), particularly for energy, starch, cereal and solid biofuel crops (Tuck et al., 2006). In these regions, yields could decline by up to 30% by the 2050s, again dependent on crop (Olesen and Bindi, 2002; Santos et al., 2002; Alcamo et al., 2005; Giannakopoulos et al., 2005; Maracchi et al., 2005). Grassland productivity is likely to be reduced by warming and precipitation changes in the Mediterranean (Valladares et al., 2005). Livestock heat stress may increase in Southern Europe, particularly in summer while decreases are anticipated for Northern Europe during winter (Maracchi et al., 2005).

There are generally fewer studies of the impact of changing climatic extremes on European agriculture. Increased yield variability (Jones et al., 2003) and reduced yields (Trnka et al., 2004) are likely to result from projected increases in heat waves and droughts (Meehl and Tebaldi, 2004; Schar et al., 2004; Beniston et al., 2007). Less information is available concerning the potential impacts of changes in extreme rainfall and flooding on the agricultural sector specifically for Europe.

An increasing demand of water for crop irrigation (up to 10%, crop-type dependent) is also likely, especially in Southern and Mediterranean regions—(Giannakopoulos et al., 2005; Audsley et al., 2006) and for fruit and vegetable production in Northern Europe (MAFF, 2000).

2.3. Impacts of climate change on water in Europe

Table 1 presents the main projected hydrological changes in Europe. A widening of water resource differences between Northern and Southern Europe is projected (IPCC, 2007b): the Central and East Mediterranean regions could experience the largest decreases and Northern Europe the largest increases in water supply from increased precipitation.

By the 2020s, annual average runoff increases of 5–15% in the North and North-west (Werritty, 2001; Andréasson et al., 2004; Falloon and Betts, 2006; Alcamo et al., 2007), and decreases of 0–23% in the South and South-East (Chang et al., 2002; Etchevers et al., 2002; Menzel and Bürger, 2002; Iglesias et al., 2005; Falloon and Betts, 2006; Alcamo et al., 2007) are projected (Fig. 3). Reductions in streamflow for the upper Danube are also projected (Mauser et al., 2006). However, climate variability is likely to have a significant effect on river runoff over this period (IPCC, 2007b). Runoff changes mostly reflect precipitation changes (Betts, 2006; Falloon and Betts, 2006), although there are differences from this trend, particularly for seasonal changes (refer to the discussion on seasonality of river flows below).

Fig. 4 illustrates the two extreme cases from the TRIP (Total Runoff Integrating Pathways—Oki and Sud, 1998) river flow model within the Hadley Centre Global Environmental Model Version 1 (HadGEM1—a version of the Met Office Unified Model MetUM—Martin et al., 2006; Johns et al., 2007), for basins where present-day predictive skill is relatively good. Decreases in the annual flow of the Douro of 40–55% and increases of up to 2% for the Pechora are projected by the 2080s (Falloon and Betts, 2006). For these basins, the baseline river flow from HadGEM1 is generally within the envelope of observed variability (Fig. 4), which is particularly wide for the Douro. A reduction in groundwater recharge is anticipated for central and eastern Europe (Eitzinger et al., 2003; Mauser et al., 2006), particularly in valleys (Krüger et al., 2002) and lowlands (Somlyódy, 2002). Higher evapotranspiration rates (Hulme et al., 2002) could also dry out soils (Falloon and Smith, 2003; Bradley et al., 2005), particularly during the summer and in continental Europe (Rowell and Jones, 2006).

The seasonality of river flow is also likely to change in some regions (Figs. 3 and 4). Earlier snowmelt in snow-dominated climates in the North could lead to earlier (but smaller) spring runoff peaks (Falloon and Betts, 2006), and increased winter runoff (Betts, 2006). This is because the warmer climate causes more precipitation to fall as rain rather than snow, which contributes to runoff more rapidly rather than being stored until next spring. In the Rhine (Middelkoop and Kwadijk, 2001), Slovakian rivers (Szolgay et al., 2004), the Volga and central and eastern Europe (Oltchev et al., 2002), higher winter flows and lower summer flows are projected. In central and Southern Europe, summer low flows could decrease by over 50% or more (Santos et al., 2002; Eckhardt and Ulbrich, 2003; Falloon and Betts, 2006). In the Alps, summer flow may initially be enhanced by glacier melt but the long-term effect could be a reduction of up to 50% (Hock et al., 2005; Zierl and Bugmann, 2005). The local characteristics of catchments can also be important—for example where groundwater is a significant component of local water budget, runoff in summer may be affected by precipitation during the previous winter (Betts, 2006).

Longer, more frequent droughts in Europe are projected as a result of warmer, drier conditions, especially in Southern, Central and Eastern Europe and the Mediterranean (Santos et al., 2002; Arnell, 2004; Alcamo et al., 2006; Lehner et al., 2006; Mauser et al., 2006). In Western Europe, climate is likely to be the main driver of increased future drought risks (Fowler and Kilsby, 2004), while increased withdrawals will likely amplify these increases in Southern and Eastern Europe (Lehner et al., 2006). Flood hazards are likely to increase across most of North, Central and Eastern Europe where projected precipitation increases are largest (Lehner et al., 2006) and decreases in flood hazard are projected for some parts of Central and Southern Europe (Dankers and Feyen, 2008). In contrast to Lehner et al. (2006), Dankers and Feyen (2008) project decreases in flood hazard in North east Europe where warmer winters and a shorter snow season reduce the magnitude of the spring snowmelt peak. However, an increased risk of flash flooding is likely for much of the region due to projected increases in intense rainfall events (EEA, 2004).

Significant increases in irrigation water demands could occur—particularly for Central, Eastern and Mediterranean Europe (Döll, 2002; Donevska and Dodeva, 2004; Bogataj and Susnik, 2007).

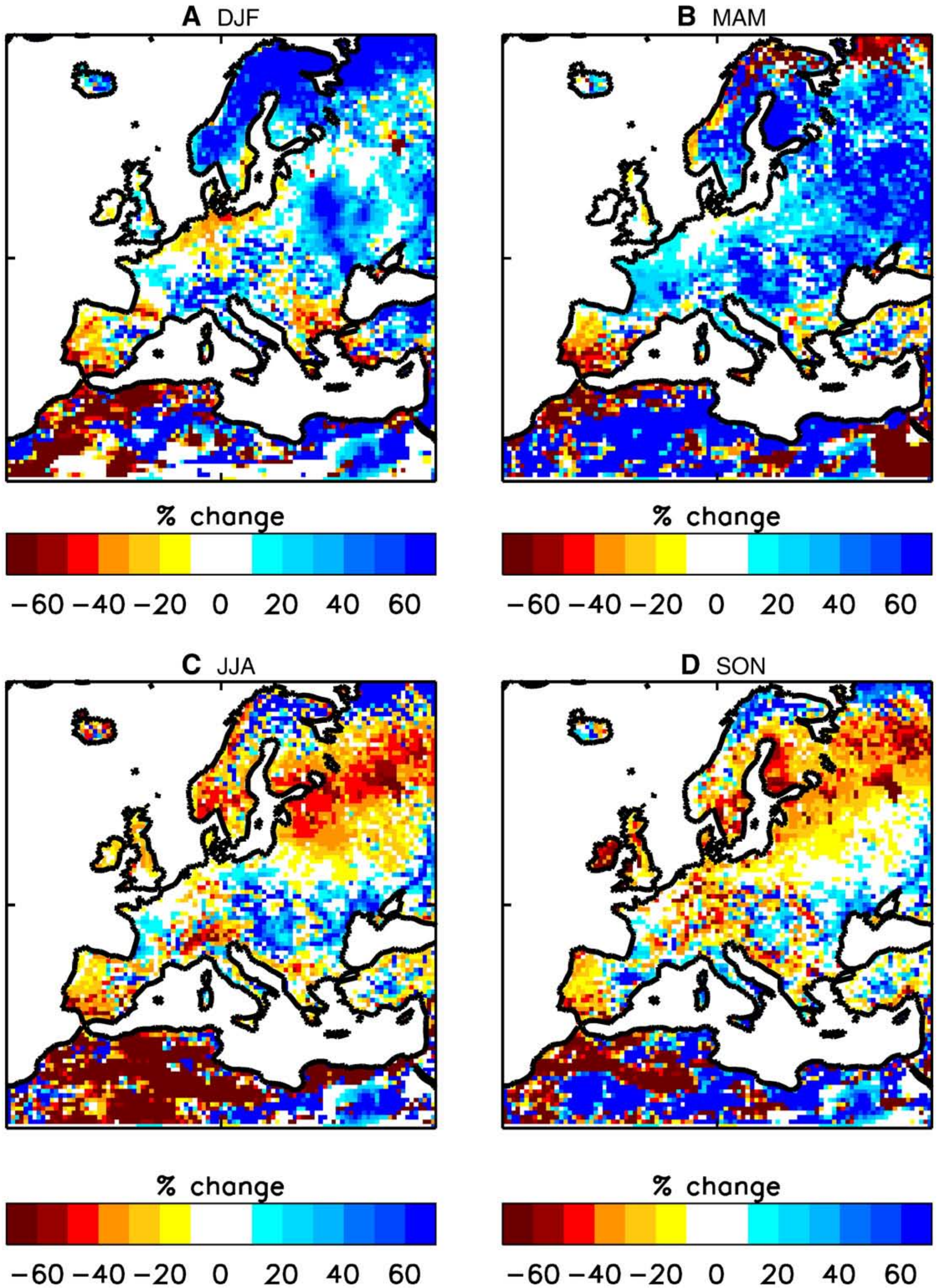

Fig. 3. Seasonal changes in runoff (surface + subsurface) for the 2080s (2071–2100) relative to the present day (1961–1990) from UKCIP02 HadRM3 regional model projections (Hulme et al., 2002) under the IPCC SRES B2 (medium-low) scenario—averages for A) December–January–February (DJF), B) March–April–May (MAM), C) June–July–August (JJA), D) September–October–November (SON).

Substantial demands may occur where they are currently very small e.g. in Ireland (Holden et al., 2003). As a result of these increases in withdrawals and climate change, competition for water and water stress are generally likely to increase in Europe (Alcamo et al., 2003; Schröter et al., 2005; Bogataj and Susnik, 2007). By the 2070s, the percentage area under high water stress in Europe is likely to increase from 19% to 35% (Lehner et al., 2001) and the number of people by 16 to 44 million (Schröter et al., 2005). Water stress is most likely to increase over Central and Southern Europe, and acute water shortages could occur in the Mediterranean, especially in summer.

3. The impact of future hydrological changes on adaptation and mitigation in European agriculture

Changes in the future hydrological cycle and climate adaptation in the water sector could have significant implications for adaptation and

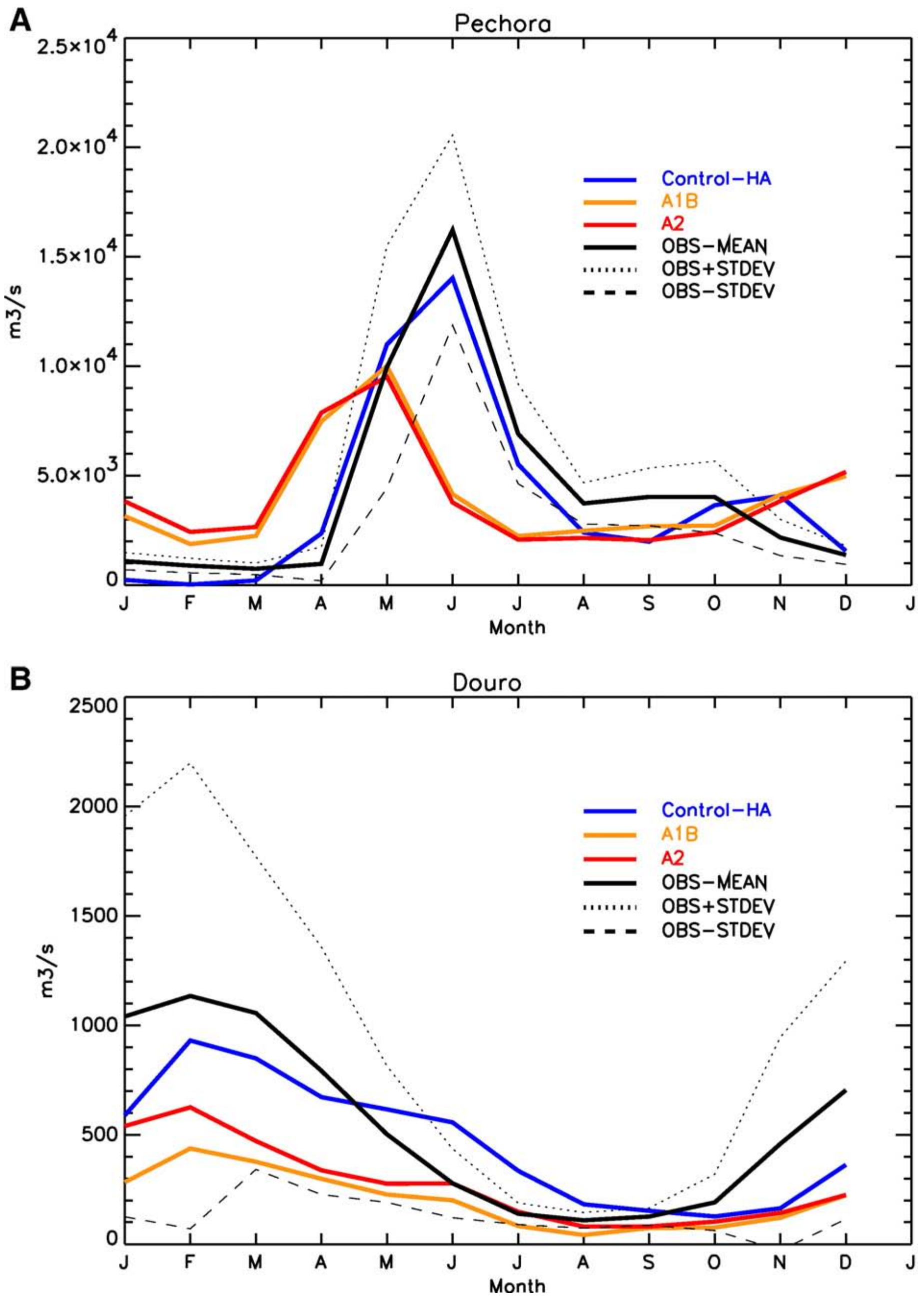

Fig. 4. Predicted changes in monthly average river flow for A) the Pechora (Russia) and B) the Douro (Portugal) from the HadGEM1 climate model for IPCC SRES emissions scenarios A1B and A2 (2071–2090) compared to a control (Control-HA) simulation including historic anthropogenic forcings (1961–1990). Data from Falloon and Betts (2006). Observational flow gauge data (mean and mean plus/minus one standard deviation) are for the Douro at Regua, Portugal (1933–1968) from Vorosmarty et al. (1998) and for the Pechora at Oksino (1916–1998) from Lammers and Shiklomanov (2006).

mitigation measures in agriculture. For instance, primary impacts could include the effects of changes in rainfall, soil moisture, evaporation, and freshwater quality and supply on the viability of future agricultural practices, and on the effectiveness of agricultural mitigation measures. Secondary impacts could also occur as a result of climate adaptation in the water sector. For instance changes in consumption patterns and competition for water between domestic, industrial and agricultural uses might alter the availability of freshwater for irrigation and other agricultural uses (Betts, 2005). As Bogataj and Susnik (2007) suggest, adaptation strategies should not be seen as individual remedies because of inter-sectoral competition for water resource allocation (Barthel et al., 2008).

Flooding also requires a cross-sectoral approach—for example urbanisation increases the coverage of impermeable surfaces (IPCC, 2007b) and thus could amplify projected increases in flood risk (de Roo et al., 2003) for small agricultural catchments. Table 1 outlines how the main projected hydrological changes in Europe might affect adaptation and mitigation in agriculture. Table 2 outlines climate adaptation measures in the water sector and their potential impacts on adaptation and mitigation in agriculture. IPCC (2008) recognises two categories of adaptation. Autonomous adaptations do not constitute a conscious response to climate stimuli, but result from changes to meet altered demands, objectives and expectations. Whilst not deliberately designed to cope with climate change, these actions may lessen the consequences of that change (IPCC, 2008). Planned adaptations result from deliberate policy decisions and specifically take climate change and variability into account (IPCC, 2008).

Table 2
Climate adaptation measures in the water sector and potential implications for adaptation and mitigation in agriculture (after IPCC, 2008)[a].

Climate adaptation measures in the water sector	Examples	Impacts on agricultural adaptation measures			Impacts on agricultural mitigation measures[b]		
		Flood resilience	Drought resilience	Area for production	CO2	CH4	N_2O
Flood protection	Structural measures: reservoirs (highlands), dykes (lowland)	+	+	+/−	−	−	+/−
	Expanded floodplains	+		−	?	−	−
	Emergency flood reservoirs	+	+?	−	−	−	+/−
	Preserved areas for floodwater	+		−		−	−
	Flood forecasting and warning systems (flash flooding)	+					
Water resources—supply side	Increasing storage capacity by building reservoirs and dams	+	+	−	−	−	+/−
	Prospecting and extraction of groundwater		+	+/−	+/−	+/−	+/−
	Expansion of rain-water storage	+	+				
	Desalination of sea water	+					
	Removal of invasive non-native vegetation from riparian areas	+	+	+	+/−	+/−	+/−
	Water transfer	+/−	+		+/−	+/−	+/−
Water resources—demand side	Improvement of water-use efficiency by recycling water and wastewater re-use	+	+		+/−	+/−	+/−
	Promotion of indigenous practices for sustainable water use	+	+		+/−	+/−	+/−
	Household and industrial water conservation	+	+				
	Reduction in water demand for irrigation by changing the cropping calendar, crop mix, irrigation method, and area planted	+/−	+	+/−	+/−	+/−	+/−
	Reduction in water demand for irrigation by importing agricultural products, i.e., virtual water	+/−	+	−?			
	Expanded use of water markets to reallocate water to highly valued uses	+/−	+/−	+/−			
	Expanded use of economic incentives including metering and pricing to encourage water conservation	+/−	+/−	+/−			
	Reducing leaky municipal and irrigation water systems	+/−	+	+			

[a] Positive effects on adaptation in agriculture are indicated with [+]; negative effects with [−]; and uncertain effects with [?].
[b] A reduction in GHG emissions is represented by a '+' since this is a positive impact.

3.1. Implications of future hydrological changes for adaptation measures in European agriculture

Table 1 summarises potential implications of changes in the future European hydrological cycle for adaptation in agriculture. As discussed in Section 2.1, decreases (increases) in water supply from precipitation in Southern (Northern) Europe will likely increase (reduce) the vulnerability of agricultural production, and reliance on abstraction for irrigation and other agricultural purposes. In Northern Europe, where increases in rainfall imply an overall excess, this could have negative impacts. Direct negative impacts of excess water include soil water-logging, anaerobicity and reduced plant growth (Bradley et al., 2005). Indirect impacts of excess water include farming operations being delayed or implemented when they could cause compaction damage such as on wet soils, e.g. livestock treading and 'poaching' (Earl, 1997; Cooper et al., 1997; Finlayson et al., 2002; Webb et al., 2005; Montanarella, 2007). Alternatively, agricultural machinery may simply not be adapted to wet soil conditions (Eitzinger et al., 2007). Similarly, increased (decreased) annual runoff in Northern (Southern) Europe will also reduce (increase) production vulnerability and increase (reduce) water available for agricultural abstraction. Reduced groundwater recharge in central and Eastern Europe could both reduce water available for abstraction and irrigation and also lead to soil salinisation (Bradley et al., 2005; ICE, 2006; Bogataj and Susnik, 2007; Montanarella, 2007), particularly in marginal areas (FAO, 2003).

Drier soil conditions (Falloon and Smith, 2003; Bradley et al., 2005) are likely, particularly during the summer and in continental Europe (Rowell and Jones, 2006) as a result of increased evaporation rates (Hulme et al., 2002). This could further contribute to greater irrigation needs and an increased risk of soil erosion (Macleod et al., 2009-this issue). In more arid regions, soil erosion is a major cause of land degradation, decreasing infiltration, water holding capacity and plant transpiration but increasing runoff and soil evaporation (Stroosnijder, 2007). However, these effects could be offset to some extent by the beneficial impact of elevated CO_2 on plant water use efficiency (Betts et al., 2007a).

Changes in seasonal river flow patterns could also have significant impacts on availability and usability of water for agricultural purposes. Decreases in summer flow in the rivers of central, Southern and Eastern Europe, the Rhine and Volga could contribute to summer irrigation shortages. Reduced water availability for summer irrigation is also a likely prospect for the Alps in the long-term. On the other hand, additional water from earlier spring runoff peaks in the North, and higher winter flows in central and Eastern Europe may not be usable depending on quality issues and provision for long-term storage (Weatherhead et al., 1997).

The projected increased occurrence and duration of droughts, particularly for Southern, Central and Eastern Europe could have many negative impacts on agriculture. These could include increased yield variability, crop stress and damage (reduced yields, increased risk of crop failures—Jones et al., 2003; Trnka et al., 2004; Gomez, 2005). Other impacts may be reduced pasture productivity, increased livestock deaths, soil erosion (via wind), and land degradation (Gomez, 2005). By reducing soil moisture recharge, stream flow and reservoir levels, drought also reduces irrigation potential (Das, 2005). Additional damage may also occur as a result of increased wildfire occurrence (e.g. Santos et al., 2002; Gomez, 2005). The 2003 heat wave in Europe had major impacts on agricultural systems, reducing quantity and quality of harvests and grassland yields, especially in Central and Southern Europe (Bogataj and Susnik, 2007; Eitzinger et al., 2007). However, as Sivakumar (2005) points out, positive aspects of drought on agriculture may arise under certain circumstances (e.g. pest reduction; snow removal in snowfall regions; introduction of long-term water conservation improvements).

Similarly, projected increases in flood risks for North, Central and Eastern Europe and for flash flooding for most of Europe present a range of challenges for agriculture to adapt to. Studies which have not included the impacts of elevated CO_2 concentrations on stomatal conductance may also underestimate future flood risks (Betts et al., 2007a). As previously mentioned, excess water in general poses problems for both soils and crops (Johnston et al., 2003; Gomez, 2005; Eitzinger et al., 2007), making conditions for production and processing unsuitable until waters recede (Sivakumar, 2005; Das, 2005; Nuñez, 2005). Additionally, flooding (as opposed to excess rainfall) can cause direct damage to (or destruction of) crops, by affecting transpiration, leaf area expansion and productivity, and increasing pest and disease problems (Das, 2005). Flooding may also increase nutrient losses (Nuñez, 2005) and soil erosion (Nearing et al., 2004; Sivakumar, 2005; Clarke and Rendell, 2007; Posthumus and Morris, 2007; Posthumus et al., 2008), and cause damage to machinery and infrastructure (Das, 2005; Nuñez, 2005).

Heavy rainfall also causes lodging of crops (Das, 2005). There may also be some positive aspects of floods, where increased water resource availability in the floodplain can be harnessed for greater agricultural productivity (Sivakumar and Stefanski, 2007), and nutrient replenishment from floodwater deposits occurs (Das, 2005). In Florida, the presence of standing water in winter reduced IR radiation loss, so could potentially prevent damaging agricultural freezes (Pielke et al., 2007). In drier regions such as Southern Europe, however, increases in intense rainfall events may also cause soil salinisation due to greater water loss past the crop root zone (van Ittersum et al., 2003); the Northern Mediterranean is particularly vulnerable to floods and soil erosion due to its climate, relief and geology (Clarke and Rendell, 2007).

In addition to the impact of these aspects of water supply on agriculture, the warming climate will likely cause significant increases in irrigation water demands (Bogataj and Susnik, 2007) which will further increase the need for drought tolerant crop and livestock systems (IPCC, 2007b), particularly in Central, Eastern and Mediterranean Europe. A map of present-day irrigated areas in Europe is shown in Fig. 5, which illustrates that irrigation is not only restricted to the drier southern regions, but is practiced quite widely. Surface water is the dominant source of water for agriculture in Greece, Spain, France, Germany, UK and Ireland; groundwater dominates in Denmark, Sweden, the Netherlands, Austria, Portugal and many coastal Mediterranean areas (Baldock et al., 2000). However, areas under irrigation may not reflect annual or seasonal intensity of water use—in the UK, the Anglian (Eastern) region accounts for over 40% of water extracted from ground and surface water for agriculture (Defra, 2008) despite a low percent area irrigated. The main sources of irrigation water also vary regionally. In Northern Italy the main source is groundwater, while in the south the use of surface water is widespread (Baldock et al., 2000).

The main secondary (or indirect) impact of hydrological changes on agriculture will be increased competition for water (Motha, 2007), particularly in Central and Southern Europe and in summer. This could potentially increase water prices, lead to more stringent abstraction and discharge controls (Environment Agency, 2007) and increase the need for water efficiency and conservation measures in agriculture.

3.2. Implications of future hydrological changes for mitigation measures in European agriculture

Adoption of agricultural mitigation options is limited by weather (both feasibility of a system and limits to NPP and decomposition) and socio-economic factors (Hutchinson et al., 2007). In light of this, Falloon et al. (2009a) discuss the potential threats and opportunities that climate change might generally pose for agricultural mitigation measures globally. Key issues included changes in: land use patterns (particularly cropland fraction), crop productivity, fraction of carbon (C) allocated below ground, and greenhouse gas (GHG) fluxes as altered by changes in controlling factors (e.g. temperature, moisture and CO_2 concentration). In conclusion, long-term reduced crop productivity and changing harvest index were considered likely to reduce C and nitrogen (N) inputs to soil. Together these factors could reduce soil carbon storage and increase GHG fluxes from agriculture globally in the absence of adaptation measures.

Table 1 summarises how future changes in the European hydrological cycle might influence the vulnerability of agricultural mitigation measures. As discussed above, a key factor will be the overall influence of changes in controlling factors on the cycling of carbon and associated GHG fluxes. For soil carbon this will depend on the balance between how changes in precipitation (and temperature and CO_2 concentration) alter crop and grassland productivity and hence C inputs to soil on the one hand, and how changes in soil moisture (and temperature) affect losses of soil C through decomposition. Additionally, the influence of management and agricultural technology can have a marked impact on these factors.

Assuming that the fraction of C returned to soil remains unchanged (and in the absence of adaptation) small mid-term increases in yield are predicted for Mid-High latitudes (IPCC, 2007b). This may lead to some small increases in C inputs to European soils over the next few decades thus increasing soil C. However in the longer term, decreasing yields would lead to reduced C inputs to soil, and thus reduced soil C storage (Falloon et al., 2009a). The widening of water supply differences in the form of precipitation in Europe is likely to lead to reduced (increased) above-ground carbon uptake in the South (North) where decreases (increases) occur, hence reducing (increasing) C

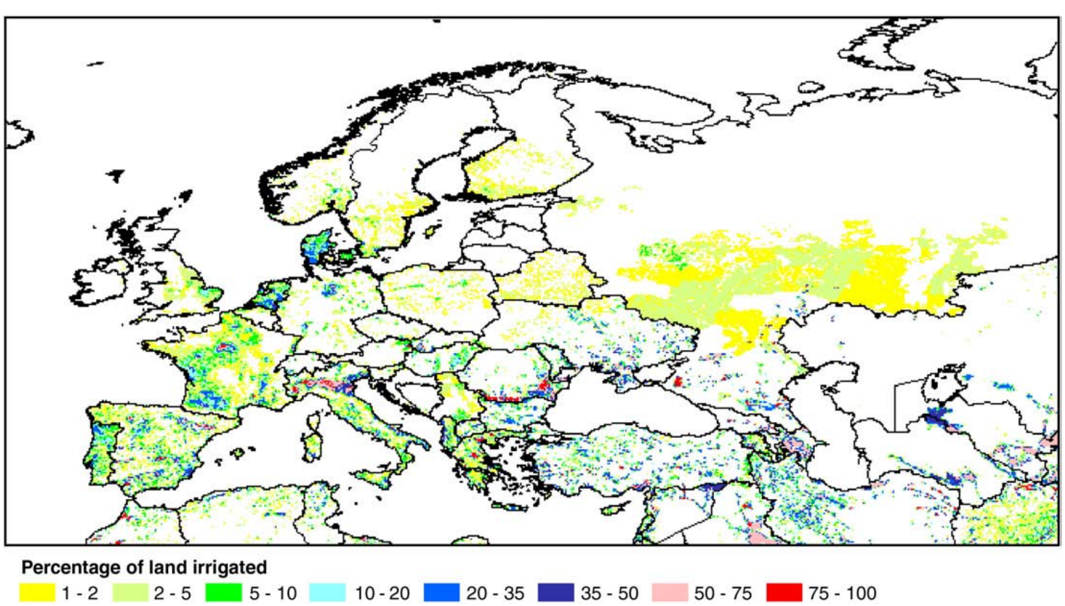

Fig. 5. Map of present-day irrigated areas in Europe (after Siebert et al., 2007).

inputs to soil and soil C storage. On the other hand, drier (wetter) conditions in the South (North) will tend to reduce (increase) soil C respiration rates. This would lead to increased (decreased) soil carbon storage because drying will reduce respiration rates (Fig. 6—Falloon, 2004; Falloon et al., 2009b).

The impact of seasonal soil moisture changes is less certain (Falloon et al., 2009b). The predicted increases in winter precipitation for Northern Europe could increase decomposition rates, leading to reduced soil C stocks where saturation does not occur. Conversely, the predicted decreases in summer precipitation for Southern Europe may act to increase soil C stocks by slowing decomposition. Higher winter rainfall totals could also increase nitrous oxide (N_2O) production and emission (Pattey et al., 2007), while excess of rainfall leading to permanent water-logging of soils may increase their methane (CH_4) emissions. Conversely the drying discussed above may lead to reduced N_2O and CH_4 emissions, but also increase carbon losses via increased soil erosion particularly through wind (Bradley et al., 2005; Clarke and Rendell, 2007; Sivakumar and Stefanski, 2007; MacLeod et al., 2009-this issue). Spring thaw can produce considerable N_2O emissions in cold climates (Pattey et al., 2007), so earlier spring thaw will likely contribute to earlier spring N_2O peaks.

How these seasonal changes balance out annually and in the long-term is complex and will depend upon the relative influence of wetting/drying patterns on GHG fluxes in each season. The global coupled climate–carbon cycle simulations of Jones et al. (2005) included interactions between climate, vegetation and the carbon cycle. Their simulations show overall decreases in soil C, especially in Southern Europe in response to an overall reduction in soil moisture although these simulations only included natural vegetation. Further analysis found that soil moisture changes alone acted to reduce (increase) soil C in Northern (Southern) Europe. In general, soil C gains due to increased NPP as a result of increased precipitation outweighed the effect of increased decomposition losses (Falloon et al., 2009b). An additional factor is the influence of elevated CO_2 concentrations on leaf conductance (Betts et al., 2007a), and hence soil moisture and GHG fluxes. Niklaus and Falloon (2006) found the C sequestration potential of a nutrient-limited European grassland to be rather limited under elevated CO_2, partly as a result of increased soil moisture.

The studies above did not include the impacts of land management and technological changes in agriculture, which could have significant impacts. For instance, land use changes and intensive cultivation could decrease soil C by up to 60% in the Mediterranean in less than four decades (Zdruli et al., 2007). The most comprehensive pan-European assessment of future changes in cropland and grassland soil SOC

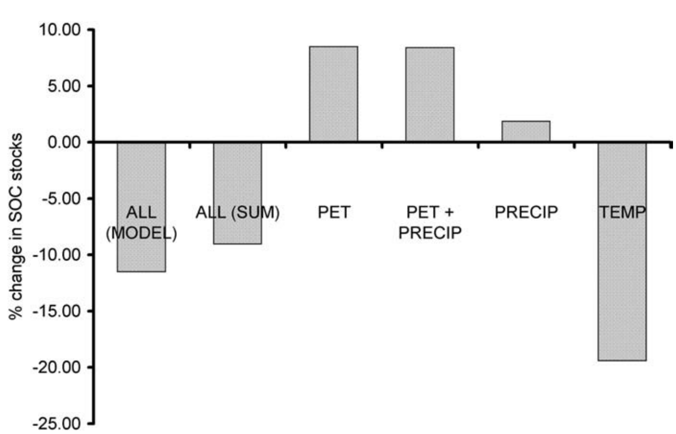

Fig. 6. The impact of climate change on UK arable soil C stocks under the IPCC SRES A1F1 scenario (HadCM3 model, 2080s) relative to present day (1961–1990) climate using the RothC soil carbon model. PET, PRECIP, TEMP = changing only potential evapotranspiration, precipitation or temperature; PET + PRECIP—changing both PET and PRECIP; ALL = changing PET, PRECIP and TEMP (MODEL) simultaneously in the model, and summing values from runs changing single climate variables (SUM).

stocks to date was performed by Smith et al. (2005). Their study considered the impacts of soil, NPP, climate change, land-use change and technology change. In agreement with the findings above, climate effects (soil temperature and moisture) were found to speed decomposition rates and cause soil carbon stocks to decrease, whereas increases in C input because of increasing NPP tended to slow the loss. Technological improvement was found likely to further increase C inputs to the soil. When incorporating all factors, cropland and grassland soils showed a small increase in soil C on a per area basis under future climate. When the greatly decreasing area of cropland and grassland were accounted for, total European cropland soil C stocks declined in all scenarios, and grassland soil C stocks declined in most scenarios (Smith et al., 2005).

However, Verge et al. (2007) suggest that decreasing population and high food consumption rate in Europe will contribute less GHG emissions from agriculture overall in the future. This could be counterbalanced by further agricultural development in Eastern Europe. Further implementation of best management practices could contribute to further reductions, including reducing livestock emissions (Verge et al., 2007).

In addition, projected changes in extractable water for agricultural purposes (particularly irrigation) in the form of groundwater or runoff will also alter mitigation potential by changing both plant productivity and decomposition. In North/Northwest (South/Southeast) Europe, improved (reduced) water availability may act to increase (limit) NPP, C inputs to soil and above ground carbon storage while soil C decomposition may be increased (limited) in wetter (drier) soils as a result of increased irrigation.

The impacts may be most marked in Central and Southern Europe where irrigation demands are projected to be greatest. If increased irrigation results in practice, then this would likely act to increase NPP and C inputs to soil but increase decomposition rates, especially during summer. While there is general consensus that irrigation leads to an overall increase in soil carbon (Follett, 2001; Lal, 2004), and possibly greater N_2O fluxes through increased soil moisture (Liebig et al., 2005), there are few studies of its overall impacts in a changing climate (Maracchi et al., 2005). However, the findings of Jones et al. (2005) and Falloon et al. (2009a,b) discussed above generally support overall increases in soil carbon as a result of irrigation.

While the introduction of drought tolerant crop and livestock systems will increase the resilience of mitigation options, they could potentially increase overall GHG emissions (e.g. the energy and fuel costs of irrigation and summer animal housing—IPCC, 2007c). Soil salinity reduces crop productivity (Amezketa, 2006) and negatively affects soil biota. Soil salinity currently affects ~1 million hectares in the European Union, mainly in the Caspian Basin, the Ukraine, the Carpathian Basin and the Iberian Peninsula (Tóth et al., 2008). Reduced groundwater recharge and increased irrigation in central and Eastern Europe may lead to increased soil salinisation (Montanarella, 2007), thus reducing NPP, C inputs to soil and potentially soil C storage.

An increase in droughtiness over Southern, Central and Eastern Europe implies a combination of threats which would likely reduce NPP. Droughty periods tend to reduce soil C gains where reduced C inputs may be slightly counterbalanced by reduced SOC decomposition (Hutchinson et al., 2007). Extreme increases in soil temperatures and drought events may also have implications for soil biological activity (Bradley et al., 2005), reducing the decomposition capability of bacteria, ultimately reducing biomass growth and soil fertility. The recent European heat wave of 2003 led to significant overall carbon fluxes from terrestrial ecosystems (Ciais et al., 2005).

The projected increased risk of flood hazards across most of North, Central and Eastern Europe and increased risk of flash flooding for much of the region implies a number of threats which could limit NPP, particularly for areas currently protected by dykes (IPCC, 2007b). Extreme wetness may reduce soil C decomposition in the short-term (Jenkinson, 1988; DeBusk and Reddy, 1998). Wet conditions in general may increase SOC gains overall since increased C inputs may slightly counterbalance increased decomposition (Hutchinson et al., 2007). Increases in intense rainfall events could also impact cropland GHG fluxes by increasing soil erosion and thus losses of soil C to watercourses (Bradley et al., 2005; MacLeod et al., 2009-this issue). Increases in intense rainfall events may also increase the occurrence of short periods of warm, wet conditions suitable for N_2O production (Falloon et al., 2009a).

In arid regions, increased salinisation due to increased water losses beyond the root zone may further reduce NPP, C inputs to soil and above ground carbon storage and negatively affect soil biota. Increased irrigation has already led to increased erosion and salinity in Mediterranean soils (Zdruli et al., 2007). There has been relatively little research into the impacts of changes in climate extremes on GHG emissions from cropland or pasture soils.

3.3. Implications of future adaptation measures in the water sector on adaptation and mitigation in European agriculture

Table 2 summarises the main impacts of future water management measures on adaptation and mitigation in agriculture—we only focus on those measures likely to have significant implications. Many flood protection and water resources measures (particularly on the supply side) present additional benefits in the form of increased flood or drought resilience for future agriculture. However, where these measures include alterations to land use (e.g. removal of invasive non-native vegetation from riparian areas) or geographic distribution of water (e.g. water transfer), and for many demand-side measures the impacts are often more complex, and may be positive or negative. For instance, in arid regions of the Southwest USA changes in vegetation, construction of dams and flood control channels within drainage networks have apparently contributed to widespread gully incision (Clarke and Rendell, 2007).

Invasive non-native species compete with natural vegetation and crops for space, nutrients and water in general thus reducing yields, decreasing water availability and contributing to land degradation (Tanner, 2007; GISP, 2008). Die-back of Himalayan Balsam (*Impatiens glandulifera*) and Giant Hogweed (*Heracleum mantegazzianum*) plants in the autumn exposes bare river banks resulting in increased erosion during high winter flows (Roblin, 1994; Wadsworth et al., 2000; Shaw and Tanner, 2008; Tanner et al., 2008). Incorporation of dead material into the water body may increase the risk of floods (Tanner, 2007; Tanner et al., 2008). Azolla (*Azolla filiculoides*) and Floating Pennywort (*Hydrocotyle ranunculoides*) can impede flood defences by forming a mat over the water body (Tanner, 2007). Climate change (in particular elevated CO_2 concentrations and increased wildfire occurrence) may additionally increase risks from invasive species (Dukes and Mooney, 1999; Dukes, 2002; Dube, 2007).

Building reservoirs and dams, or providing preserved areas for floodwater will reduce land available for agricultural production at the site of the new reservoir. However, productive capacity may be increased over a wider agricultural area. Increased groundwater extraction might increase the area of potentially productive land on the one hand, but reduce it on the other where salinity problems occur as a result of irrigation. Reducing agricultural irrigation demands (e.g. introducing crops with higher water use efficiency) could act to increase flood risks if evaporative losses remain low compared to conventional systems since this would leave more runoff on the land surface, particularly during periods of intense rainfall and excess water. The impacts of measures involving economic incentives and trading (e.g. pricing, markets and importing agricultural products) on adaptation within a region are complex and harder to predict.

Water management measures can also have implications for GHG emissions in the agricultural sector (IPCC, 2008)—and thus on the mitigation potential of different options (Table 2). Here, we do not consider the wider implications of water management on overall GHG emissions (e.g. transport, energy use) since these are discussed in IPCC (2008), but focus on the land–water related aspects.

The impact of new dams or reservoirs on net GHG emissions, whether for water resources, flood protection or hydropower remains highly uncertain (IPCC, 2007c, 2008) and is affected by location, flow rate, size and type. Most reservoirs emit small amounts of CO_2 due to carbon naturally carried by water (Tremblay et al., 2005). However, some temperate and boreal reservoirs absorb CO_2 at the surface (UNESCO, 2006). Natural floodplain emissions of CH_4 may be reduced by oxidation in the reservoir water column (e.g. Huttunen, 2005). However, there are generally few studies of GHG emissions for European reservoirs and the temperate zone in general (IPCC, 2007c, 2008).

More recent data from a global analysis of large temperate dams found them to be a net methane source (Lima et al., 2008). Observations from Swiss lowland, sub-alpine and alpine reservoirs found them to be net emitters of CO_2 and CH_4, but not N_2O (Diem et al., 2008). However, lowland Swiss lakes (Diem et al., 2008) and a Finnish boreal lake (Huttunen et al., 2003) have been found to be small potential sources of N_2O and the range of emissions of all GHGs across lakes is large (Diem et al., 2008; Del Sontro et al., 2008). In addition to the aforementioned factors, the overall net GHG flux will also depend on pre-damming emissions. Key factors include whether soils in the catchment are a net source or sink of GHGs, and whether they are naturally flooded or not (Guérin et al., 2008). Rotting vegetation and inflows from the catchment can be responsible for considerable GHG fluxes (IPCC, 2008). The major sources of nitrogen responsible for N_2O fluxes from dams are agricultural fertilizers and urban waste discharges from the upstream watershed (UNESCO, 2006). Dissolved organic matter can also contribute around half of the CO_2 emissions from boreal reservoirs (Soumis et al., 2007).

There is little directly comparable data available, but CO_2 emissions from European reservoirs (860 ± 700 mg m^{-2} d^{-1}—Diem et al., 2008) are similar to, or slightly exceed net carbon fluxes for European grasslands and arable lands (520 and 843 mg m^{-2} d^{-1} respectively—Vleeshouwers and Verhagen, 2002). CH_4 emissions from European reservoirs (0.2 ± 0.15 mg m^{-2} d^{-1}, but much higher due to ebullition at one site—Diem et al., 2008) generally exceed those of agricultural land (negligible for arable soils, which tend to be a net sink—Goulding et al., 1995) excluding livestock, although riparian wetland areas could emit considerably more: 0–1290 mg m^{-2} d^{-1} (Sovik et al., 2006). N_2O emissions from reservoirs are generally small ($<72 \pm 22$ µg m^{-2} d^{-1}—Diem et al., 2008) compared to European agricultural land and riparian wetland zones (0.57–6.57 mg m^{-2} d^{-1} and -0.12–9.9 mg m^{-2} d^{-1} respectively—Machefert et al., 2002; Sovik et al., 2006). We have assumed that emergency flood reservoirs would likely have similar (but lesser) impacts to large reservoirs.

Creating preserved areas for floodwater and expanded floodplains will increase the area of land which is temporarily or permanently inundated. In turn, this will likely increase emissions of both CH_4 and N_2O relative to the original agricultural land (Machefert and Dise, 2004; Sovik et al., 2006), depending on the original management and N loading. Methane emissions could be further increased by climate change (Gedney et al., 2004). Since water table depth can have a marked impact on GHG fluxes from soils (Flessa et al., 2006), increased extraction of groundwater could have either positive or negative impacts depending on the original water table depth and soil type. Irrigative use of water extracted from groundwater is generally likely to increase both agricultural productivity and respiration of soil carbon resulting in an overall increase in soil carbon (Follett, 2001; Lal, 2004). However, increased soil moisture under irrigation may cause greater N_2O fluxes (Liebig et al., 2005).

As for agricultural adaptation, the impact of several water management measures on mitigation in agriculture is likely to be complex. For instance, the removal of non-native invasive vegetation from riparian areas could increase or decrease mitigation potential depending on the nature of the original and invasive vegetation, and their overall impacts on GHG fluxes (Pyke et al., 2008) although there are few studies to confirm this. However, it is feasible that annual invasive species such as Himalayan Balsam may increase GHG fluxes relative to natural vegetation via autumn vegetation dieback, which may increase carbon losses via erosion when soils are bare. Secondly, dieback may contribute dead vegetative material to water bodies giving rise to GHG emissions on decomposition. Water transfer, and reducing water demands for irrigation by importing agricultural products may both indirectly affect the nature of agricultural production within a region, and hence mitigation potential between regions.

Practices which involve improved water use efficiency, promotion of indigenous sustainable water use practices, and reductions to irrigation demands are generally likely to increase productivity and residue returns to soils, and reduce losses through erosion (Rosenzweig and Tubiello, 2007; Madari et al., 2005), increasing soil carbon storage (Follett, 2001; Lal, 2004). Similar impacts may be expected for reduced tillage and increased residue return (e.g. Cerri et al., 2004), which also reduce decomposition rates through lower aeration, disturbance and soil temperatures (Hutchinson et al., 2007). On the other hand, since these practices will likely reduce evaporative losses and increase soil moisture (Hutchinson et al., 2007), increased emissions of CO_2 and N_2O and may result (West and Post, 2002; Alvarez, 2005; Gregorich et al., 2005; Ogle et al., 2005). The impact of tillage on N_2O remains uncertain (Marland et al., 2001; Cassman et al., 2003; Smith and Conen, 2004; Helgason et al., 2005; Li et al., 2005).

In the humid regions of Europe, drainage of croplands may increase agricultural productivity and thus soil carbon (Monteny et al., 2006). The impacts of drainage on N_2O fluxes could be either positive or negative (Reay et al., 2003) depending on the balance between improved aeration reducing emissions and N loss (and subsequent

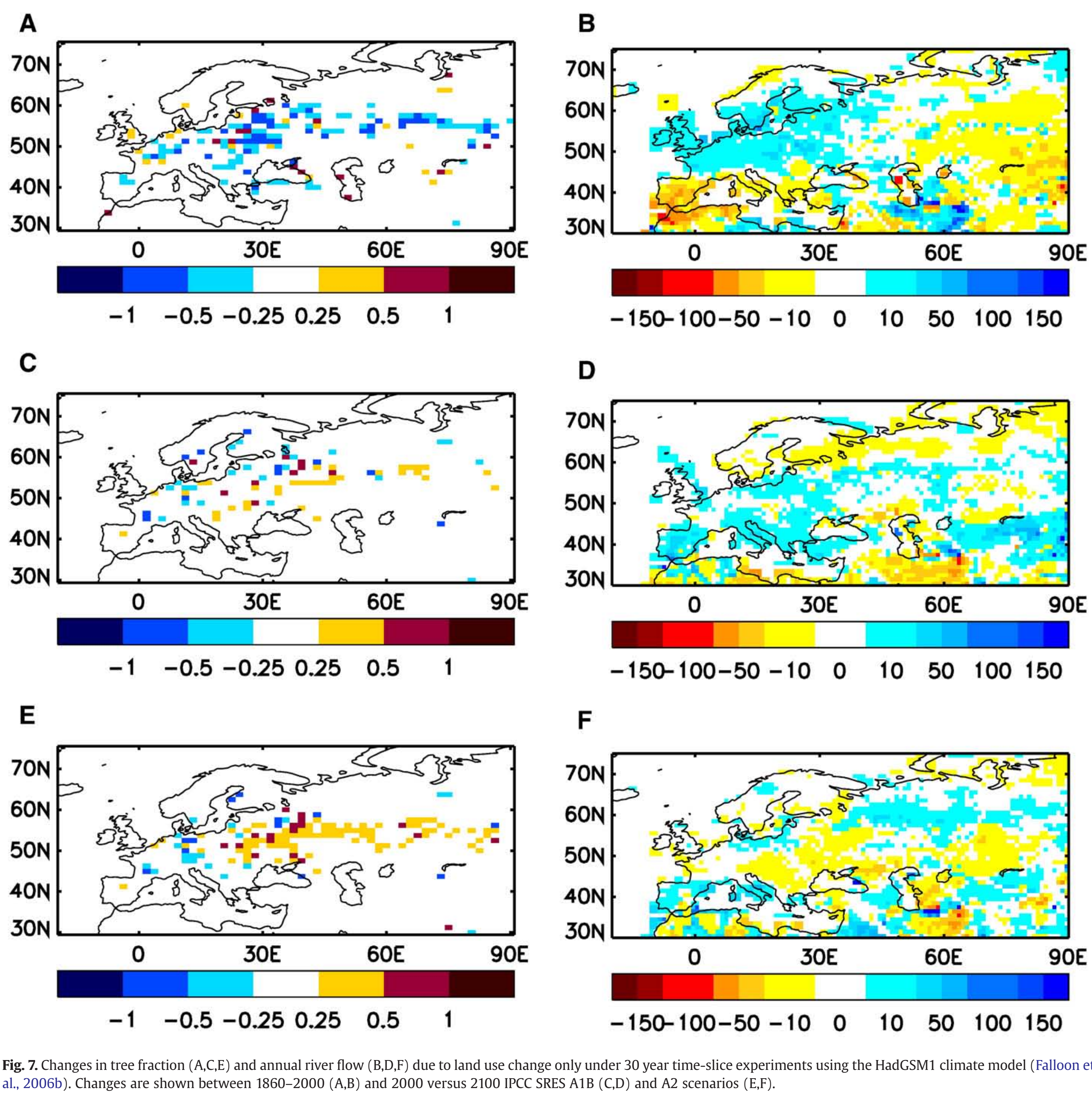

Fig. 7. Changes in tree fraction (A,C,E) and annual river flow (B,D,F) due to land use change only under 30 year time-slice experiments using the HadGSM1 climate model (Falloon et al., 2006b). Changes are shown between 1860–2000 (A,B) and 2000 versus 2100 IPCC SRES A1B (C,D) and A2 scenarios (E,F).

denitrification) in drainage water (IPCC, 2008). Water (and crop) management in rice systems could significantly alter GHG fluxes (Betts, 2005; Guo and Zhou, 2007)—paddy rice management is a significant contributor to global climate feedbacks.

4. Interactions—the importance of an integrated approach

Feedbacks and interactions between agro-ecosystems and climate are often highly non-linear and non-additive (Betts, 2006). Although our study has not focused on the impacts of specific agricultural mitigation and adaptation options on future hydrology in detail, some general concepts are discussed below.

A number of biophysical climate forcings may result from altered land and water management. For instance, elevated CO_2 concentrations may reduce crop transpiration and hence increase runoff rates (Betts, 2005; Betts et al., 2007a). The impact of elevated CO_2 concentrations has been detected in continental runoff records (Gedney et al., 2006), including those for Europe. Rising CO_2 concentrations could also increase global mean runoff more through physiological forcing of transpiration than radiatively forced climate change. Because of this, in regions where radiatively forced climate change does not significantly increase local precipitation such as Southern Europe, increased runoff may still result (Cramer et al., 2001). Significant changes in regional cropping patterns in response to climate change may also alter the local and regional climate by modifying the nature of the land surface (Betts, 2005). Key factors will include changing roughness length and albedo. Different crops will also have different transpiration responses to elevated CO_2 concentrations. The overall regional hydrological responses to land use change and elevated CO_2 concentrations may also significantly from local changes (Tenhunen et al., 2009), making scaling up challenging.

Betts et al. (2007b) found that land use conversion to agriculture led to local cooling in temperate regions due to an increase in albedo during winter and spring. Historic land clearance for agriculture may have increased river flows over Western Europe (Fig. 7—Falloon et al., 2006b) particularly during the summer (T. Kasikowski, pers.comm.), while future afforestation could have the opposite effect. During the growing season, ecosystem water conditions can also significantly alter surface albedo in grasslands through their impact on plant growth and ecosystem conditions (Wang and Davidson, 2007). Soil albedo usually increases when water content decreases and vegetation growth is strongly controlled by water conditions in semi-arid systems. In the winter season, precipitation (snow) amount greatly affects surface albedo of grasslands. Higher albedo during dry years could therefore alter moisture flux convergence and rainfall, causing a positive feedback and drier climates as a result. Changing land management practices within agricultural land uses could also alter the climate—for instance Seguin et al. (2007) found that windbreaks modified albedo and surface roughness length.

Wattenbach et al. (2007) found that afforestation of abandoned European agricultural land had a negative impact on the regional water balance. For 100% afforestation of abandoned croplands, increases in evapotranspiration were particularly marked during spring (>25%). Reductions in the annual sum of groundwater recharge of up to 30%, and in the annual sum (peak) of runoff of up to 5% (20%) were found. In contrast, changing tree species from Scots Pine to Common Oak decreased the annual sum of evapotranspiration by 3.4%, increasing annual groundwater recharge by up to 9% and annual total runoff by up to 2%.

Land surface processes and properties, such as erosion and SOC cycling may also be altered by changing land management, which may have complex impacts. As previously discussed, changes in SOC stocks are likely to occur as a result of the changing climate, and altered land and water management practices. The most comprehensive study currently available (Smith et al., 2005) suggests small per-area increases in SOC are likely, although this did not consider the impact of adaptation and mitigation practices other than land use and technological change. There is little information on the impact of SOC loss on soil productivity (Montanarella, 2007). However, reduced SOC content may reduce water infiltration due to changes in soil structure and hence increase flood risk. Conversely, increasing SOC content increases water holding capacity (Franzleubbers and Doraiswamy, 2007)—Hoogmoed et al. (2000) found a strong positive relationship between infiltration as a percentage of rainfall and SOC in Sahelian soils. Fig. 8 shows the potential impact of changes in SOC content from the coupled climate–carbon cycle simulations of Jones et al. (2005) on available water content (Huntington, 2006) although these only include climate-induced changes to natural ecosystems. Pimentel et al. (1995) studied erosion impacts on crop productivity finding annual losses of SOC had a minor effect on available water content, but were linked to substantial increases in runoff; in the longer-term cumulative SOC losses resulted in larger available water content reductions which reduced grain yield. Low SOC contents also increase vulnerability to soil erosion (Dube, 2007), particularly in arid regions. Increased soil erosion in Europe is likely to result from drier summers (mainly via wind) and increased heavy rainfall events (mainly via water). Soil erosion can further reduce water retention capacity and infiltration, lowering available water contents and grain yields

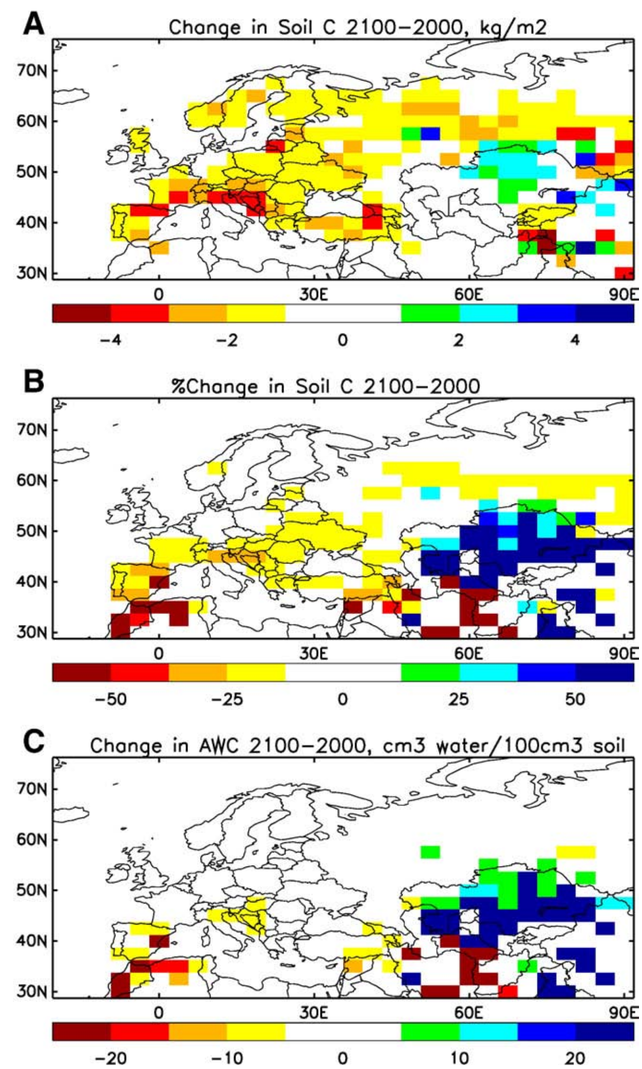

Fig. 8. Changes in soil carbon content (as A) kg C m^{-2} and B) %) and C) resulting changes in available water holding capacity (AWC—cm^3 water per cm^3 soil) by 2100 relative to 2000 from the RothC soil carbon model driven by HadCM3LC coupled-climate carbon cycle model projections (Jones et al., 2005). Changes in AWC calculated according to Huntington (2006).

(Pimentel et al., 1995), but also increasing runoff and flood risk (Montanarella, 2007). Land degradation and soil erosion can also lead to siltation which may reduce reservoir capacity, further increasing flooding risks (Dube, 2007).

Drier European summers will also increase fire risks, particularly in Southern Europe. By leaving soil bare and exposed to sunlight, wind and water, fires increase soil compaction, reduce water content and infiltrability (Sivakumar and Stefanski, 2007). In turn, these changes can increase soil erosion and land degradation, increase runoff and flood risk during wet periods, increase dry season drought severity, reduce groundwater recharge and increase the loss of nutrients (Nuñez, 2005; Gomez, 2005; Dube, 2007). Resulting impacts include damage to cultivated fields (Nuñez, 2005) and reduced agricultural production (Das, 2005).

Specific management practices can also cause complex changes to agro-ecosystems and their environments. For instance, under irrigation, inadequate drainage can cause water logging and salinisation (Sivakumar, 2007). Salinisation can also increase soil albedo, and a secondary problem is the dispersion of sodic soils which may reduce infiltration capacity (Sivakumar, 2007) and water retention (Montanarella, 2007). In this way, salinisation can reduce soil fertility, cause significant yield losses, and result in increased runoff and damage to water supply infrastructure (Montanarella, 2007).

These examples demonstrate that changes to the management of agricultural land and water resources to meet climate adaptation or mitigation aims are likely to have complex effects. Changing agricultural and water management practices could affect climate at a range of scales (local, regional or global), and by different mechanisms (biophysical and geochemical), and modify land surface process and properties, which could in turn alter agricultural productivity. Therefore, in order to fully assess alternative land and water management practices a holistic approach is required to avoid unintended negative impacts and to maximise potential benefits (Kundzewicz and Somlyódy, 1997; Hansen et al., 2006; Barthel et al., 2008; Krysanova et al., 2007; Mahmood et al., 2007; Wattenbach et al., 2007).

5. Uncertainties and research gaps

Uncertainties in climate impacts on agriculture and water management can arise from a number of sources. Key factors include uncertainties in socio-economics and the GHG emissions scenarios derived from them and both the changes in future climate and their impacts as a result (Hansen et al., 2006; Betts, 2006). These factors are usually assessed using a range of emissions scenarios based on different assumptions (e.g. IPCC SRES, 2000), a range of different climate models, ensembles of individual climate models where uncertain parameters are altered (e.g. Murphy et al., 2004), and a range of different impacts models. Fig. 9 demonstrates uncertainties in future European river flows from one of these sources (Betts et al., 2006)—the TRIP river flow model (Oki and Sud, 1998) driven by data from the perturbed parameter climate model ensemble of Murphy et al. (2004). Considerable uncertainty in both present-day and future river flow projections arise due to uncertainty in climate model parameters. The climate sensitivities (global climate response to doubling CO_2) in the ensemble members used here (4.1, 2.9, 3.6 and 7.0 °C for members 3, 4, 11, and 12 respectively) result in changes in annual river flow under doubled CO_2 ranging from +20 to +71% for the Pechora and −14 to −62% for the Douro. In general, the impact of future changes in precipitation on adaptation and mitigation in agriculture is particularly uncertain since future predictions of precipitation are less certain than future changes in temperature (IPCC, 2007a; Falloon et al., 2009a,b).

Since simulation models are the most commonly used tools for climate impacts assessments, the skill of both climate and impacts models needs to be considered, implying that robust evaluation will be particularly important. Critical components include climate variability and scale (both spatial and temporal—Betts, 2005). For example, while GCMs simulate the atmosphere on a sub-daily time step, their coarse spatial resolution and resulting distortion of day-to-day variability may limit the direct use of their daily output for agricultural impacts studies (Hansen et al., 2006). There is a strong relationship between the North Atlantic Oscillation (NAO) and landslides in Portugal (Trigo et al., 2005), but since conventional atmospheric models have limited skill for the NAO (e.g. Scaife et al., 2005) this may limit current and future erosion predictability.

At the other end of the scale, Burt et al. (2008) emphasise the need to assess the impacts of management changes over an appropriate time period—particularly for agro-ecosystem processes where the long-term effects and slow response times are important. For instance, catchment nitrate concentrations may not respond to management changes for some 20 to 30 years. Farmers need information at local scales to enable robust adaptation planning (Betts, 2006) although most climate projections for Europe are typically available at scales too coarse for this (e.g. 25–50 km resolution). The limited spatial and temporal scale of conventional climate model projections is potentially problematic for predicting 'impacts' processes such as soil erosion, water resources, hydrology and nutrient loss which often require information at much finer scales (Kundzewicz and Somlyódy, 1997). More detailed information is also needed in order to accurately simulating the impacts of partial land use change on climate (Betts, 2006), which may differ considerably to widespread uniform changes. Similarly, the response of regional hydrology to climate and land use change will depend on how local changes scale up to the region (Tenhunen et al., 2009).

Making impacts assessments more robust (and less uncertain) also requires an improvement in the understanding and representation of processes and management practices. Firstly, climate impacts studies often take a linear approach, separately modelling each system in turn which neglects the important and complex feedbacks and interactions demonstrated here (Betts, 2006). Appropriately representing these interactions, and including water resources in integrated climate–agro-ecosystem models may therefore be key to predicting future impacts (Kundzewicz and Somlyódy, 1997; Hansen et al., 2006; Krysanova et al., 2007; Mahmood et al., 2007). Processes and interactions requiring particular attention in impacts assessments include—physiological and hydrological responses of vegetation to elevated CO_2, local landscape and water budget changes and interactions with climate (e.g. Barthel et al., 2008; Wattenbach et al., 2007), ensuring consistency between projected local climate changes and the nature of cropland which would arise as a result, and better representation of crops and management practices in climate models (Betts, 2005; Mahmood et al., 2007). There are also very few comprehensive impacts assessments of (or models for) organic soils (Smith et al., 2005; Falloon et al., 2006a). Current models may overestimate N_2O fluxes, and the timing, duration and magnitude of peaks caused by fertiliser applications and rainfall events (Calanca et al., 2007). As noted above, more integrated approaches may also improve local climate predictions—the inclusion of seasonal vegetation in a climate model was found to improve skill for seasonal precipitation (Lawrence and Slingo, 2004).

For adaptation and mitigation strategies, there is also a need to consider potential management responses to these uncertain changes in climate and their impacts, and the resulting effects (Schaldach and Alcamo, 2006). Currently, assessment of the wider impacts of individual land management practices including both geochemical and biogeophysical forcings are very limited (Desjardins et al., 2007; Mahmood et al., 2007). Specifically, there is very little information on the impacts of land use changes on water resources other than conversion of agriculture to forest (Krysanova et al., 2007; Wattenbach et al., 2007; IPCC, 2008), or on the impact of different management practices (notably burning and grazing) on albedo.

Since climate impacts themselves are often affected by socio-economic and land use changes, there is also a need for consistency in

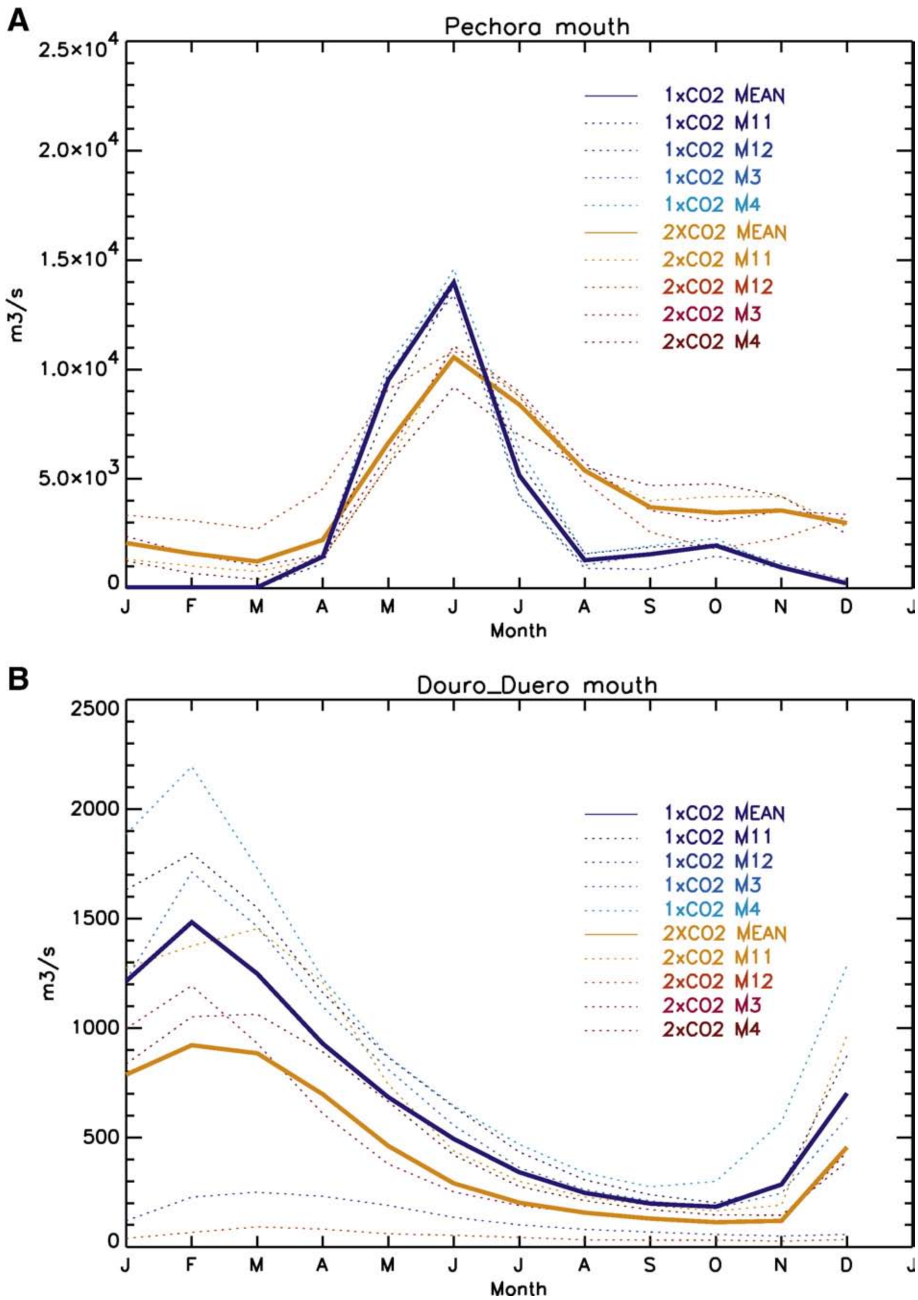

Fig. 9. Impact of doubling CO_2 on seasonal pattern of river flow for A) the Pechora (Russia) and B) the Douro (Portugal) basins under 4 HadSM3 climate model ensemble members from the Quantifying Uncertainty in Model Projections project (QUMP—Murphy et al., 2004). Blue dashed lines show individual $1 \times CO_2$ members, red-orange dashed lines show individual $2 \times CO_2$ members. Means of individual members are shown as solid lines.

the application of socio-economic, land use, emissions and climate data to impacts assessments (Henseler et al., 2008). There is also a need for better integration of water cycle–ecosystem–climate models with socio-economic simulations (e.g. Messner et al., 2007; Barthel et al., 2008). For instance, Krysanova et al. (2006) found that socio-economic changes have potentially impacted regional water resources in East Germany and Poland more significantly than climate change in the recent past, although climate will likely exert a stronger influence in the coming decades.

While in general impacts assessments have advanced from simple sensitivity studies (e.g. doubling CO_2) to more complex scenarios (e.g. IPCC SRES, 2000)—there is now need to consider more complex scenarios and interactions (Betts, 2006), such as climate stabilisation scenarios which may better reflect realistic storylines for the coming decades. Socio-economic drivers and technological changes can potentially overcome agricultural production limitations due to changes in climate (Eitzinger et al., 2007). Finally although weather is the main source of uncertainty for crop production in Europe due to its highly intensive nature (Bogataj and Susnik, 2007), climate is only one aspect of agricultural risk (Hay, 2007; Hertzler, 2007). In light of the many sources of potential uncertainty discussed above the development of robust ways of applying uncertain climate information to agricultural decision making (e.g. hedging, foreclosing options, creating new options and diversification—Hay, 2007; Hertzler, 2007) will be critical in planning resilient future land management options.

6. Conclusions

We have reviewed projected changes in climate and its impacts on agriculture and water in Europe. General trends include northward movement of crop suitability zones and increases in crop productivity in Northern Europe, but declining productivity and suitability in Southern Europe. This may be accompanied by a widening of water resource differences between the North and South, and an increase in extreme rainfall events and droughts. Changes in future hydrology and water management practices will influence adaptation measures in agriculture, and alter the effectiveness of agricultural mitigation strategies. Many of these interactions are highly complex and influenced by a number of factors which are themselves influenced by climate. Mainly positive impacts may be anticipated for Northern Europe, where agricultural adaptation may be shaped by reduced vulnerability of production, increased water supply and reduced water demand. However, increasing flood hazards may present both direct and indirect challenges for agriculture in Northern Europe, and summer irrigation shortages may result from earlier spring runoff peaks in some regions. Conversely, the need for effective adaptation will be greatest in Southern Europe as a result of increased production vulnerability, reduced water supply and increased demands for irrigation. Increasing flood and drought risks will further contribute to the need for robust management practices in Southern Europe.

The impacts of future hydrological changes on agricultural mitigation in Europe are more complex, and will depend on the balance between changes in productivity (and hence C inputs to soil) and rates of decomposition and GHG emission, both of which depend on climatic, land and management factors. In general, small increases in European SOC stocks per unit land area are anticipated considering changes in climate, management and land use, although an overall reduction in the total SOC stock may result from a smaller agricultural land area. However, the most comprehensive study available to date (Smith et al., 2005) on which these findings were based did not explicitly include adaptation measures.

Changing water management regimes in Europe will also affect adaptation and mitigation in agriculture. In general, adaptation in the water sector will likely provide net benefits to agricultural production such as reduced flood risk and increased drought resilience. However, the impacts of some water management measures (such as removal of invasive non-native species from riparian zones and economic incentives) on agriculture are more complex and harder to predict.

The two main sources of uncertainty in climate impacts on European agriculture and water management are future climate projections and the impact of these changes in climate on water and agriculture. In the latter sense, since changes in climate, agricultural ecosystems and hydrometeorology depend on complex interactions between the atmosphere, biosphere and hydrological cycle there is a need for more integrated approaches to climate impacts assessments for agriculture and water (Betts, 2005, 2006; Desjardins et al., 2007; Pielke et al., 2007). A more comprehensive representation of agriculture in climate models should therefore allow more robust quantification of the past, current and future impacts of agriculture on climate and vice versa (Desjardins et al., 2007).

However, there are significant challenges in achieving this aim, including issues of scale and biases in both climate and agro-ecosystem models. Future projections of changes in precipitation are also critical in this respect, but remain highly uncertain. Processes and management practices subject to considerable uncertainty, or where few detailed studies have been performed include: the impact of moisture changes on SOC storage and GHG fluxes; the impact of climate extremes on mitigation potential and GHG fluxes (particularly floods and droughts, and for pastures); the impacts of extreme rainfall and flooding on agricultural production in Europe; agricultural mitigation estimates which explicitly consider adaptation practices; the implications of removal of invasive non-native species on hydrology and GHG emissions; GHG emissions from European reservoirs; and the impacts of economic incentives in the water sector for agricultural production.

Integrated assessment approaches could be further enhanced and used to provide benefits beyond a more complete understanding of the role of agriculture in the Earth system. For instance, Seguin et al. (2007) and Desjardins et al. (2007) suggest that rather than considering simply mitigation potential, research should be directed towards options which "moderate" the overall impact of agriculture on climate, including both GHG fluxes and geochemical and biophysical interactions with climate. This in turn requires a better representation (and understanding) of specific management practices in integrated assessment tools. However, as well as more holistic 'within-sector' assessments, a 'cross-sector' approach may also be needed, considering risks to food, energy and water supplies (Pielke et al., 2007) regionally and globally. For example, the availability of water for irrigation may be affected by both changes in runoff as a direct consequence of climate change, and by climate-related changes in demand for water for uses in other sectors (Betts, 2005). Furthermore, crop management activities such as irrigation may affect other impacts sectors such as water resources or flood risk.

Increasing food consumption trends in the future will likely increase the need for enhanced European agricultural production, further increasing pressure on the environment (Verge et al., 2007) and natural resources. This supports the need for a better understanding of climate impacts on sustainable agriculture (Motha, 2007), rather than simply considering the effectiveness of agricultural adaptation or mitigation practices alone. While there is no accepted 'universal' definition of sustainable agriculture, the three principle goals are environmental quality, economic profitability and socio-economic equity. Methods for assessing options which "moderate" the impact of agriculture in the wider sense will therefore need to consider socio-economic aspects alongside a better physical and biological understanding of the agro-ecosystem in a changing environment.

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