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Current and future irrigation water requirements in pan-Europe: An integrated analysis of socio-economic and climate scenarios

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ABSTRACT

Irrigated cropland plays a crucial role for agricultural production but has also been identified as a major user of global freshwater resources. The amount of irrigation water needed depends on climate conditions and socio-economic factors (e.g. amount of crop production and technology). In this study we analyze the development of irrigated area and the corresponding net irrigation water requirements for pan-Europe using a spatially explicit land-use model (LandSHIFT) together with a hydrology and water-use model (WaterGAP3). Four simulation experiments for the assessment of irrigation water requirements were conducted: (1) irrigated area for the base year 2000 under climate normal conditions, (2) irrigated area for 2000 with two climate scenarios for 2050, (3) two scenarios for changing irrigated area until 2050 under climate normal conditions and (4) the two irrigated area scenarios in combination with the climate scenarios. Results show that under baseline conditions yearly irrigation water requirements sum up to 53 billion m^3. The expansion of irrigated area strongly depends on the combination of socio-economic drivers and climate change. Generally, the two analyzed climate scenarios lead to an expansion of irrigated area which we explain by negative effects of increasing air temperatures on crop growth conditions. Analysing the irrigated area scenarios and climate scenarios separately, we find that the effect of land-use change on net irrigation water requirements is larger than the climate effect. Combined analysis of socio-economic and climate drivers reveal that the expansion of irrigated area is not directly correlated to the changes of irrigation water requirements as the adaptation of sowing dates to the changing climatic conditions might help to overcome seasonal water deficits. The study underlines the importance of considering both the change of irrigated area and agricultural management as well as hydrology aspects in regional water use analysis and shows that simulation models can serve as tools to provide this information to the development of regional water management strategies.

1. Introduction

The main water demand in agro-ecosystems is posed by the evapotranspiration process of the cultivated crops (Falkenmark and Rockström, 2006). As in many parts of the world precipitation is not sufficiently available to sustain crop yields, irrigation plays an important role to provide additional water. In the year 2000 more than 30% of the global crop production was generated on irrigated areas which account for almost 24% of the total global cropland (Portmann et al., 2010). At the regional level large differences can be observed. While in Northern Africa irrigated area accounts for about 30% of total cropland, in Europe this share is not larger than 7%, mainly located in the Mediterranean and Black Sea regions. Consequently irrigation is responsible for a large part of human freshwater consumption and therefore stands in direct competition to other human activities such as households and industries (Alcamo et al., 2003). Hence, estimates of the future spatial extent of irrigated area and the resulting irrigation water requirements are important information for the development of scenarios of freshwater futures.

Rain-fed as well as irrigated crop production is affected by environmental and socio-economic factors. One important environmental factor is climate change (e.g. Parry et al., 2004; Schlenker and Lobell, 2010). This includes changes of air temperature as well as an increase of atmospheric CO_2 concentrations which might have adverse effects on crop yields (Long et al., 2006). Furthermore, changing geographic and seasonal precipitation patterns might have significant impacts on local water availability. For Europe, Olesen and Bindi (2002) give an overview of possible climate effects on agriculture. They come to the conclusion that it is likely that air temperatures increases might lead to an increasing water demand for irrigation purposes. Also, in Northern Africa and the Middle East, lower precipitation in combination with higher air temperatures is very likely to result in an additional demand for irrigation water (Döll, 2002). The most important socio-economic factor is the globally growing demand for food and fiber, primarily posed by an increasing world population and changing

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diets (Rosegrant et al., 2008). Crop production can be increased either by expanding the cultivated area or by intensifying crop management, e.g. by the use of fertilizer, machinery and irrigation measures. Again, as Foley et al. (2011) point out in their analysis, there is no universal global picture. For example, against the global trend of expanding cropland area, the European Union (EU) and many parts of the former Soviet Union are facing a decline of cropland area driven by market mechanisms, agricultural policy and/or mismanagement.

In order to account for the effects of environmental and socio-economic factors on irrigation water requirements in large geographical regions, spatially explicit simulation models have proofed to be valuable tools. There are several model-based studies that analyze irrigation water requirements for a static distribution of irrigated area, for example on the global scale (Döll, 2002; Rost et al., 2008), for Europe (Wriedt et al., 2009a,b), or for China (Thomas, 2008). Information on the spatial distribution of irrigated area is available for area equipped for irrigation (Siebert et al., 2007) and for real irrigated area (RIA), which is lower by definition. A global RIA map has been produced by Portmann et al. (2010) while a map for Northern Africa and Europe has been constructed by Aus der Beek et al. (2010). On the other hand land-use models are well established scientific tools for calculating the future spatial distribution of agricultural land (Heistermann et al., 2006; Schaldach and Priess, 2008). For Europe, the CLUE model is used to calculate high-resolution land-use scenarios (Verburg et al., 2008). However, this approach does not explicitly account for changes in irrigated area. The combined effects of land use and climate change on evapotranspiration from cropland and water use for irrigation were analyzed for the African continent by Weiß et al. (2009). They have applied a land-use model in combination with a hydrological model, but expansion of irrigated area was not modelled in a spatially explicit manner and irrigation water requirements were calculated only for two crop types (non-rice and rice). These approaches show that, in order to provide a more accurate assessment of future irrigation water requirements, the following aspects need to be considered: (1) the change in spatial extent of irrigated area, (2) the type of crop allocated to this area (since the water requirements vary strongly between different crop types) and (3) climate change, which affects precipitation as well as evapotranspiration during the growing season.

The objective of this study is to give a model-based estimate of the future development of irrigated area for pan-Europe and to investigate the effects of changes in climate and agricultural production on irrigation water requirements. As pointed out earlier, the aim is to improve the integrated analyses of regional water stress and to support the development of sustainable management strategies of land and water resources (Kämäri et al., 2008). In order to simulate these combined effects, we have integrated a new component for the spatial allocation of irrigated area into an existing land-use model which is then coupled to a model that calculates the resulting crop irrigation water requirements. In the first step, we analyze the irrigation water requirements for the crop production on irrigated area in the year 2000. In the second step, we conduct model experiments for different scenarios with a time horizon of 2050, taking into account the effects of changes in crop production on the extent and spatial pattern of irrigated area and of climate change on crop irrigation water requirements.

2. Materials and methods

2.1. Regional settings

The regional settings for our study were developed within the EU FP-6 project SCENES which addresses the complex questions about the future of freshwater resources in Europe and its neighbouring states up to 2050 (Kämäri et al., 2008). The study region covers pan-Europe, an area including the Mediterranean rim countries and reaching from Caucasus to the White Sea in the East (Fig. 1). In order to analyze regional differences, it is further subdivided into seven regions according to the UN classification: NA (Northern Africa), WE (Western Europe), NE (Northern Europe), SE (Southern Europe), EEc (Eastern Europe, central), EEe (Eastern Europe, eastern), and WA (Western Asia). The spatial extent of the outer SCENES regions, as for example in Russia and Egypt, has been derived from river basins, and therefore does not agree with national borders.

2.2. Scenarios

2.2.1. Socio-economic scenarios

According to Alcamo (2008) we define scenarios as plausible descriptions of how the future may unfold. Within the EU SCENES project, four narrative storylines, namely Economy First (EcF), Fortress Europe (FoE), Policy Rules (PoR) and Sustainability Eventually (SuE) were developed. Their aim is to provide a reference point for long-term strategic planning of pan-European freshwater resources. The methodology for scenario development is based on the SAS (Story-And-Simulation) approach, linking storyline revision and modelling work as an iterative process (Alcamo, 2008). The qualitative scenarios were created within a participatory scenario development process in pan-European panels (PEP). They describe a set of plausible futures, both the socio-economic and environmental settings, and possible consequences for water quantity and quality in pan-Europe mainly as narrative storylines. The group of stakeholders included representatives from the private sector, policy, scientists, and non-governmental organizations, thus covering a broad range of expertise on water-related issues. Altogether around 35 persons were involved in the scenario development process out of which 12–15 participated in any of the scenario workshops (Kock et al., 2011). The quantitative scenarios provide numerical data based on modelling results taking up information on drivers from the storylines and questionnaires filled out by panel participants. Consequently, the scenarios provide a consistent set of alternative socio-economic assumptions for the year 2050 which allows us to explore a wide range of future developments in our analysis. The most important socio-economic drivers for the model experiments presented in this study are information on future agricultural development, comprising the amount of crop production (irrigated and rainfed) and the influence of technological change on achievable crop yields. As part of the quantitative scenarios this data has been calculated by the integrated ecological, economic, and socio-demographical policy model AEZ–BLS (Fischer et al., 2002, 2005). It combines a detailed spatial agro-ecological zone model (AEZ) that covers all countries and a regionalized general equilibrium model of world food economy (BLS). The fraction of irrigated production of each crop has been derived for the year 2000 from the IFPRI database (Rosegrant et al., 2008) and is kept constant during the simulation period.

The four SCENES scenarios were classified into reference (EcF and FoE) and policy scenarios (PoR and SuE) which reflect different views of the future. In order to explore a wide range of potential future development pathways in particular of the agricultural sector, we have chosen one representative scenario from each group for our experiments:

(1) Economy First (EcF): in this scenario, the economy develops toward globalization and liberalization, so innovations spread but income inequality, immigration and urban sprawl cause social tensions. Global demand for food and bio-fuels from Europe drives the further industrialization of agriculture with large farm units. As the Common Agricultural Policy (CAP) is weakened and subsidy payments are drastically cut-off, farms are abandoned where crop production is uneconomic. Until 2050 technological change allows potential increases of crop yields by 23% within the countries of the EU (EEc, NE, WE, SE). Countries located in the other regions (EEe, NA, WA) only achieve a 14% potential increase. These values reflect the scenario inherent inequality between regions and represent a

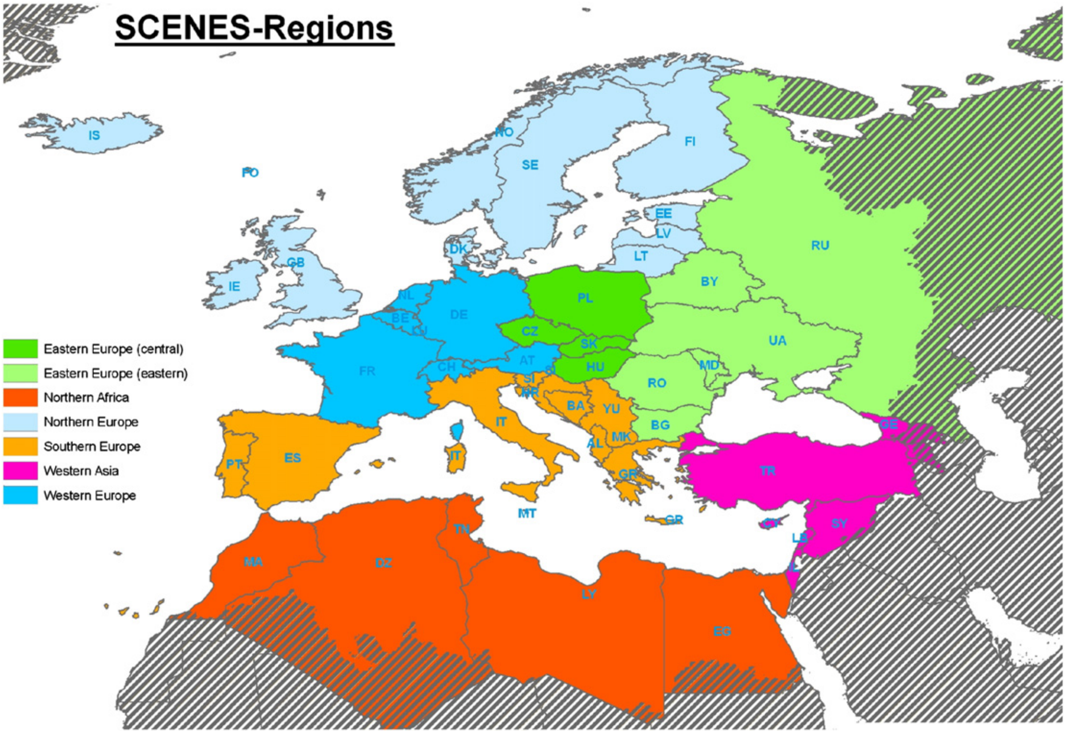

Fig. 1. Study region pan-Europe.

rather pessimistic view on future crop yield developments (e.g. Jaggard et al., 2010). In the scenario context this can be explained by decreasing investments in R&D efforts in the agricultural sector due to the stop of subsidy payments and relatively low world market prices. Nevertheless, total crop production is growing by 29% (from 981.890 kt to 1.266.157 kt). While the EU is exporting agricultural goods to the world market, the other countries predominantly aim at fulfilling their domestic food demand. NA has the largest increase (+155%) followed by WA (+88%) and NE (+20%). Only for EEc a decrease of crop production by −4% is assumed. Future trends in population and economic activity show a further increase of population by 32.5% (348 million people) for pan-Europe until 2050. Here, the highest growth rates are expected in NA and WA while the population increase in Europe is rather moderate. Economic activity continues to grow over the whole scenario period resulting in an 86% growth in GDP.

(2) Sustainability Eventually (SuE): Europe transforms from a globalized, market-oriented to an environmentally sustainable society, where local initiatives are leading. Landscape is the basic unit and there is a strong focus on quality of life. Direct agricultural subsidies are phased out and replaced by policies aimed at environmental services by farmers, such as support for farmers in less favourable areas with high-nature value farmland and accompanied by effective spatial decentralization policies. Land-use changes in general promote greater biological diversity. In order to spare land for nature (e.g. Ewers et al., 2009) crop yields are assumed to potentially increase by 50% until 2050 in all regions. This assumption reflects the conservative scenario by Jaggard et al. (2010) with yearly crop yield increases of around 0.7%. Former regional inequalities are reduced by technology transfer from the EU to other parts of pan-Europe. At the same time total crop production is increasing by 6.9% (from 981.890 kt to 1.049.608 kt) with large regional differences. While crop production is doubling in NA and other regions with continuous population growth, there is a decrease of −21% in EEe as exports of agricultural goods to the world market are substantially reduced. Population is expected to increase only by 13% (143 million people) in pan-Europe between 2000 and 2050. For Europe, a decrease in population is projected whereas for NA and WA the population continues to grow. Compared to EcF, the SuE scenario shows a lower development of total GDP with an increase of only 14% between 2000 and 2050.

2.2.2. Climate data and scenarios

Climate data is used for the LPJmL and WaterGAP3 model runs to calculate potential crop yields and irrigation water requirements (see Section 2.3). Climate forcing data applied in this study has been compiled from station data and regionalized by the Climate Research Unit (CRU) of the University of East Anglia, Norwich, U.K. (version TS 2.1, Mitchell and Jones, 2005). CRU data covers the time period from 1960 to 2000 westwards of 32°E in 10′ (about 15×17 km) and eastwards of 32E in 0.5° resolution (about 46×50 km) and in monthly time steps, providing nine climatic parameters, e.g. precipitation, air temperature, cloud cover, etc. All climate data has been rescaled to the 5 arc minute grid for WaterGAP3 model runs. Here, the internal water balance calculations are being conducted in daily time steps, for which all climate data, except precipitation, has been interpolated with cubic splines to daily values. Precipitation data is being converted to daily time steps by taking into account the number of rain days per month featuring a Markov chain algorithm (Geng et al., 1986).

As all SCENES storylines address potential future climate impacts, the socio-economic scenarios are combined with the IPCC SRES A2 emission scenario to account for the effect of climate change until the year 2050. Under this scenario, the atmospheric CO_2 concentration increases up to 492 ppm (IPCC et al., 2007). The most recent available global climate model datasets are those from the 4th assessment report (AR4) and accessible via the Climate Scenario section of the Data Distribution Centre (DDC) of the Intergovernmental Panel on Climate Change (IPCC). Results from different global climate models were compared. In order to represent the variability between these models, the climate output from two General Circulation Models (GCMs) was chosen as input for the model calculations within this study. Both selected scenarios show a high increase of temperature but have large differences in precipitation thus representing “dry” and “wet” climate conditions which are likely to have strong effects on irrigation water requirements (Table 1):

(1) IPCM4: the IPSL-CM4 model has been developed by the Institute Pierre Simon Laplace, France (Fichefet and Morales Maqueda, 1997; Madec et al., 1998; Goosse and Fichefet, 1999; Hourdin et al., 2006). Under the A2 scenario it indicates high air temperature increase over large parts of Europe in spring (March, April, May), i.e. of 2 °C to 3 °C in Southern and Central Europe and up to 5 °C in Northern and Eastern Europe. During the summer season (June, July and August) temperature is expected to increase between 3 °C and 4 °C across Europe. At the same time by using this GCM, low precipitation change (increase or decrease) in Europe is expected (”dry” scenario).

(2) MIMR: the MIROC3.2 model is from the Center for Climate System Research, University of Tokyo, Japan (K-1 model developers, 2004). The A2 scenario is comparable with IPCM4 and projects a high temperature increase over Europe but in combination with a precipitation increase or low decrease (”wet” scenario). Air temperature increases across Europe by 2 °C to 3 °C in spring with highest increases in Northern Europe (up to 5 °C). Southern, Northern and Eastern Europe will face a temperature increase of 3 °C to 4 °C in summer, whereas for large parts of Western Europe this increase will be up to 3 °C. By comparing both GCMs, air temperature turned out to be slightly higher in the IPCM4 output, especially in Southern France and Northern Spain.

The original GCM outputs have a spatial resolution of 1.875°×1.875° (T63). For our analysis monthly temperature (T) and precipitation (P) have been downscaled to a 5 arc minute grid with a simple bilinear interpolation approach. Scenario climate data provided for the LPJmL and WaterGAP3 models is generated by scaling standard gridded data sets of mean monthly precipitation and temperature from the baseline period (see Section 2.4) with the differences between current and future conditions as computed by the climate models (delta change approach, e.g. Henrichs and Kaspar, 2001; Lehner et al., 2006). Temperature data are scaled by addition and precipitation data by multiplication. An exception to this rule occurs when present-day precipitation is close to zero (<1 mm); in this case the respective precipitation rise is added. By applying this approach, data describing the long-term average future trend in climate were combined with data describing current climate variability. In this case the spatial information density of the coarse resolution GCM output is improved by scaling the values with the high resolution dataset from the Climate Research Unit CRU (Mitchell and Jones, 2005). The number of rain days per month and the cloudiness are taken from the reference period (1961–1990). Then, monthly temperature and precipitation data is converted to daily time steps as described above.

Table 1
Change in annual average temperature (T) and precipitation (P) between baseline (1961–1990) and future (2040–2069) under the IPCC-SRES scenario A2 represented by two GCMs (IPCM and MIMR).

Region	Change in annual average T [°C]	Change in annual average P [%]
IPCM4		
Northern Africa	>1–4	<−30–>+30
Western Europe	>2–3	−15 to −5
Northern Europe	>2–5	No change–+30
Southern Europe	>2–3	−15 to −5
Eastern Europe (central)	>3–4	−15–no change
Eastern Europe (eastern)	>3–5	−30–+15
Western Asia	>2–3	−30 to −5
MIMR		
Northern Africa	>2–4	<−30–>+30
Western Europe	>2–3	No change–+15
Northern Europe	>2–5	+5–+30
Southern Europe	>2–3	−15–no change
Eastern Europe (central)	>3–4	No change–+15
Eastern Europe (eastern)	>3–5	No change–+15
Western Asia	>2–4	−30 to −5

2.3. Modelling framework

Computations of changes of irrigated area and irrigation water requirements are carried out by soft-linking the spatially explicit land-use model LandSHIFT and the hydrology and water use model WaterGAP3, i.e. the models are run in a sequential order. Input data on country level includes irrigated crop production in metric tons based on the SCENES scenarios. Starting with this information, LandSHIFT computes the spatial change of irrigated cropland area between 2000 and 2050. The resulting raster maps serve as input to the irrigation water use calculations of WaterGAP3. In the following the individual models are described.

2.3.1. Modelling the change of irrigated area

The land-use model LandSHIFT is fully described in Schaldach et al. (2011) and has been tested in different world regions (e.g. Lapola et al., 2010; Alcamo et al., 2011). The model is based on the concept of land systems (Turner et al., 2007) and couples components that represent the respective anthropogenic and environmental sub-systems. In our study, we have included components to simulate the change of irrigated area (IRRI-module) and crop productivity (productivity-module). Changes of irrigated area are calculated on a uniform raster with a cell size of 5 arc-minutes (~6×9 km in Central Europe). Each cell is characterized by the state variables “dominant land-use type”, and “fraction of irrigated area” as well as by a set of parameters that describe its landscape characteristics (e.g. terrain slope), available road infrastructure and zoning regulations.

Information on crop productivity of each grid cell is derived from raster maps displaying the potential yields under irrigated conditions for 10 crop types, calculated with the dynamic global vegetation model LPJmL (Sitch et al., 2003; Bondeau et al., 2007) under the baseline climate conditions and for the different climate scenarios (Section 2.2). This data serves as input to the IRRI-module where it is used for suitability assessment and to define the amount of crop production that can be allocated to each raster cell. As LPJmL does not cover all crop types necessary for our analysis, they are mapped to the respective LandSHIFT crop types (Table 2).

Input data for the IRRI-module is provided on country level. It comprises the amount of irrigated production of 12 major crop types (Table 2) and information on crop yield improvements due to technological change as defined by the socio-economic scenarios. The latter information is used to adjust the crop yields generated by the productivity-module. The rational of the IRRI-module is to simulate changes of irrigated area in each country in pan-Europe by distributing the irrigated crop production to the most suitable raster cells by modifying the two aforementioned state variables. The respective algorithm is displayed in Fig. 2. In phase 1, the algorithm determines the suitability of each raster cell for irrigated crop cultivation, considering the parameters potential crop yield (generated by LPJmL), terrain slope, population density and road infrastructure. Furthermore, nature conservation areas are excluded from being converted into irrigated cropland. The spatial allocation of crop production (phase 2) is computed with a modified version of the Multi Objective Land Allocation (MOLA) algorithm (Eastman et al., 1995; Schaldach et al., 2011). First, the production of each crop is distributed to the most suitable raster cells with already existing irrigated area (as indicated by the state variable "fraction of irrigated area"), and their state variable "dominant land-use type" is set to the respective crop type. If not all of the crop production can be allocated on the existing irrigated area, additional land has to be converted to irrigated cropland (phase 3). This preferably takes place on raster cells where irrigated area is already located. Here, the existing "fraction of irrigated area" is expanded proportionally to the number of irrigated raster cells of the crop type under consideration. If after this allocation step crop production is still left, new raster cells have to be converted, where so far no irrigated area is located. For this purpose, preferably cells with area equipped for irrigation (Siebert et al., 2007) are considered. Here, the amount of irrigated area that is allocated to the best suited raster cells is proportional to the local area equipped for irrigation. Results are raster maps with two types of information: (1) the area of irrigated cropland on each cell in km^2 (state variable "fraction of irrigated area") and (2) the crop type which has been allocated there (state variable "dominant land-use type").

2.3.2. Modelling irrigation water requirements

The impact of climate and land-use change on irrigation water requirements is calculated with the global hydrology and water use model WaterGAP3 (Alcamo et al., 2003; Flörke and Alcamo, 2004; Verzano, 2009). A detailed description of the irrigation module of Water GAP3 is given by Döll and Siebert (2002). Major model inputs are climate data and the raster maps with the location of irrigated area and the allocated crop type provided by the LandSHIFT model (see above). Annual net irrigation water requirements are calculated for each irrigated raster cell in a two-step procedure:

In the first step, WaterGAP3 determines the sowing date of each growing season. Here, the most suitable 150-day period within each modelled year is being chosen, based on air temperature and precipitation criteria taken from Allen et al. (1998). The temperature criterion ensures continuous energy supply and optimal growing conditions, whereas the precipitation criterion promotes water supply and aims to prevent cropping periods during drought conditions. If both criteria allow for a second 150-day growing period within the same year, it directly follows the first period (double cropping). Within the current model set-up double cropping is carried out with an identical crop type as the spatial crop distribution generated by LandSHIFT remains constant within a year, which is an important simplification. Moreover, the assumption of a growing period of 150 days is reasonable for crops such as vegetables, potatoes, pulses, wheat, barley, maize, rice and fruits, but underestimated for fibers and winter wheat, and overestimated for fodder plants (Smith, 1992).

Table 2
Mapping of crop types between LandSHIFT and LPJmL.

LandSHIFT crop type	LPJmL crop type
Wheat	Temperate_cereals
Rice	Rice
Maize	Maize
Other cereals	Temperate_cereals
Root crops	Temperate_roots
Sugar crops	Sugar_cane
Pulses	Pulses
Oil seeds/crops	Max (Sunflower, Rapeseed, Groundnuts)
Fruit	Mean (Maize, Temperate_roots)
Vegetables	Mean (Maize, Temperate_roots)
Stimulants	Mean (Maize, Temperate_roots)
Fibers and tobacco	Mean (Maize, Temperate_roots)

In the second step the net irrigation requirements for each irrigated raster cell are being calculated based on the CROPWAT approach (Smith, 1992):

$$\begin{aligned} I_{net} &= k_c * E_{pot} - P_{eff} && \text{if } E_{pot} > P_{eff} \\ I_{net} &= 0 && \text{if } E_{pot} \le P_{eff} \end{aligned}$$

with

I_{net} = net irrigation requirement per unit area [mm/d]
P_{eff} = effective precipitation [mm/d]
E_{pot} = potential evapotranspiration [mm/d]
k_c = crop coefficient [–]

E_{pot} is being computed accordingly to Priestley and Taylor (1972) as a function of net radiation and air temperature, which Weiß and Menzel (2008) have identified as the most suitable method for large scale hydrological applications.

As described in Aus der Beek et al. (2011) k_c values feature a crop specific distinctive distribution curve throughout the growing period and are closely related to LAI development (Liu and Kang, 2007), as they mimic plant development. Each crop has three to four different development stages during its 150-day growing period: nursery (rice only), crop development, mid-season, and late-season. For example, the barley k_c increases between day 1 and 120 from 0.3 to 1.2, and then decreases until day 150 to 0.25. As k_c curves vary within different climatic regions of pan-Europe, different k_c values for arid and humid grid cells have been incorporated in the model.

2.4. Modelling procedure

2.4.1. Model initialization

The initial land-use map of LandSHIFT is based on the CORINE 2000 database (EEA, 2007) for the EU-27 countries. Land use data for the remaining pan-European countries (for spatial extent see Fig. 1) is taken from Heistermann (2006), who provides a crop specific version of the GLCC land-use map. Both, CORINE and GLCC have been harmonized to eighteen classes and aggregated to 5 arc-minutes spatial resolution. Information on the fraction of irrigated area on each cell and the respective crop distribution is based on the map of real irrigated area (RIA) for 2000 developed and tested in Aus der Beek et al. (2010).

The LandSHIFT routines for suitability assessment and for land allocation use raster-level information on landscape characteristics, zoning regulation and land-use related model variables. Population density is derived from the global HYDE database (Klein Goldewijk, 2005) while data on terrain slope is derived from the HYDRO1k data set (USGS, 1998). The information on road infrastructure is assessed via the VAMP0 data set on roads (NIMA, 1997). In order to derive information of zoning regulation, we map the raster cells to data sets on areas designated as national or international nature conservation areas (WDPA Consortium, 2004).

2.4.2. Model evaluation

Modelled gross irrigation water requirements with WaterGAP3 were successfully evaluated for Europe in Aus der Beek et al. (2010). Generally, WaterGAP3 model results showed only 1% deviation from reported total European irrigation water requirements, whereas discrepancies between modelled and observed values were higher for some European countries. Additionally, in Aus der Beek et al. (2011) the functionality of the crop-specific calculation of irrigation water requirements was assessed for Central Asia, which showed a good fit between observed and modelled values for wheat and cotton for the entire simulation period (1958 to 2002).

2.4.3. Model experiments

For this study, we have designed four model experiments using the previously described modelling framework. The aim is to assess the effects of climate change and socio-economic developments on the spatial extent of irrigated area and the resulting irrigation water requirements.

(1) Model Experiment 1 – "Baseline" – computes irrigation water requirements for a reference climate period (1961 to 1990). Information on climate, irrigated area and level of technology are based on year 2000 data.
(2) Model Experiment 2 – "Climate change 2050" – takes into account only the impact of climate change on irrigation water requirements. Irrigated area and level of technology are set to year 2000 values.
(3) Model experiment 3 – "Land-use change 2050" – considers land-use change (in terms of irrigated area) due to changing socio-economic drivers and its effect on irrigation water requirements. Climate data is taken from the reference period.
(4) Model Experiment 4 – "Climate change and land-use change 2050" – analyses land-use change and its effect on irrigation water requirements under climate change.

For each model experiment a set of simulation runs has been conducted, taking into account the respective combination of socio-economic drivers from the EcF and SuE scenarios and the climate change data from the two GCMs.

3. Results

In the following, the results from the simulation experiments are described. The analyzed model outputs include the change of irrigated area (LandSHIFT) and the resulting crop irrigation water requirements (WaterGAP3).

3.1. Change of irrigated area

Changes of irrigated area between 2000 and 2050 were calculated as part of the model experiments 3 and 4 (Table 3) whereas in the remaining experiments this area is kept constant. Model experiment 3 comprises two simulation runs which solely take into account the socio-economic drivers from the EcF and SuE scenarios in form of irrigated crop production and technological change while climate data has been taken from the reference period (1961–1990). On the pan-European level, under the EcF scenario irrigated area increases by 18% from 181.202 km^2 to 214.028 km^2 while in the SuE scenario irrigated area is shrinking to 162.305 km^2 (−10.5%), respectively. Only in two regions, Northern Africa (NA) and Northern Europe (NE), irrigated area is growing under both scenarios. At the same time Eastern Europe (central and eastern) and Southern Europe (SE) are facing a decrease of irrigated area. Generally, the area increases are higher and decreases are lower in the EcF scenario compared to the SuE scenario. For Western Asia (WA) and Western Europe (WE) the model calculates opposite trends with increasing irrigated area under EcF and decreasing area under SuE.

Model experiment 4 includes four simulation runs combining each of the socio-economic scenarios with the two climate change scenarios provided by the IPCM4 and MIMR GCMs. As an example, Fig. 3 shows the spatial distribution of irrigated area in the base year and for the EcF simulations with different climate inputs.

Under the "dry" climate scenario (IPCM4), both for EcF and SuE an increase of irrigated area is calculated, but with a large discrepancy between the two (+73% and +8.8%, respectively). Under EcF, irrigated area is increasing in all regions with hot spots being located in WE (+282%), NA (+77%) and SE (+45%). In contrast, under SuE the extent of irrigated area is declining in EEe, SE and WA.

For the "wet" climate scenario (MIMR) in combination with the EcF socio-economic scenario, we find a relatively similar but less pronounced result, with irrigated area expanding by +54% in total. Compared to the model runs with IPCM4 climate, also a slight decrease of irrigated area in SE can be observed. The MIMR input together with the SuE scenario results in area increases in NA and WE while irrigated area is shrinking in all the other regions.

Comparing the results from the two model experiments we can identify two trends: First, there is a generally stronger increase of irrigated area under EcF than under SuE due to the influence of the socio-economic scenario drivers (model experiment 3). Second, analysing each socio-economic scenario separately, this trend is strengthened by

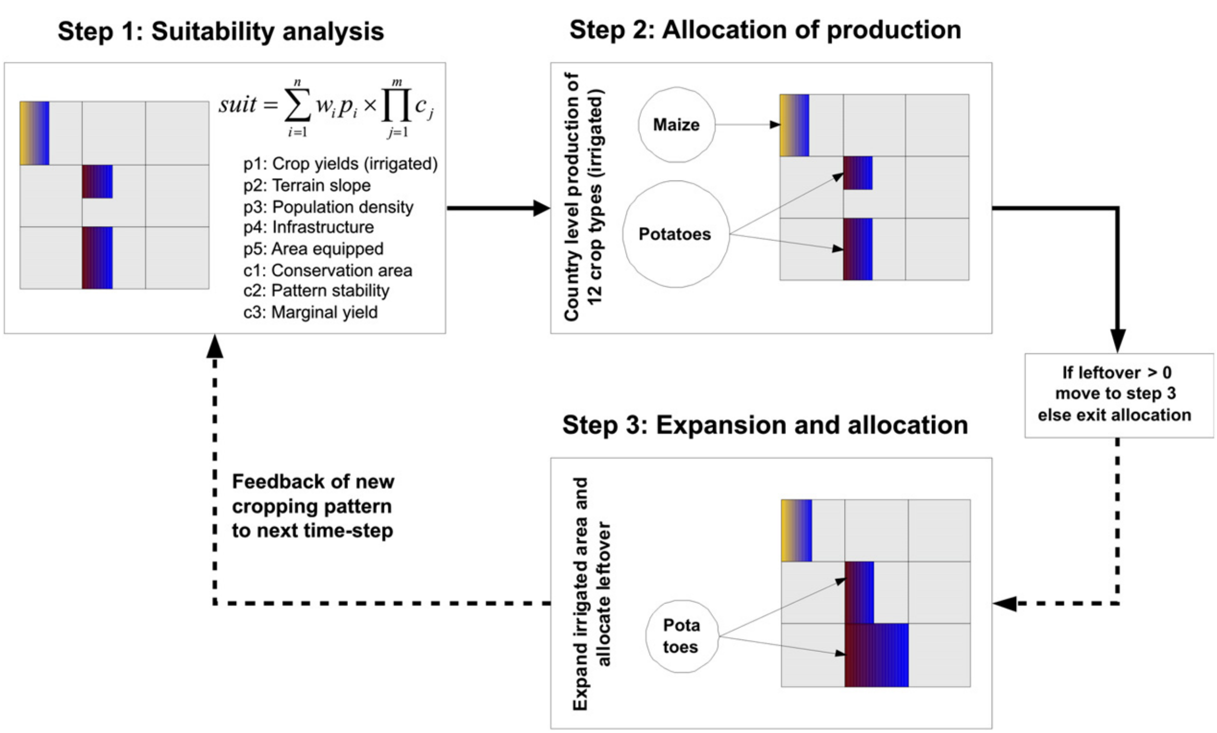

Fig. 2. Block diagram of the LandSHIFT irrigation sub-module (IRRI).

Table 3
LandSHIFT simulation results: irrigated area in km^2 in 2000 (baseline) and 2050.

Model experiment	1	3		4			
Climate forcing	Base 61–90	Base 61–90	Base 61–90	IPCM4 2050	IPCM4 2050	MIMR 2050	MIMR 2050
Land use	Base 2000	EcF 2050	SuE 2050	EcF 2050	SuE 2050	EcF 2050	SuE 2050
Eastern Europe (central)	2456	1747	1544	4315	2698	5084	2963
Eastern Europe (eastern)	19,015	16,136	10,721	25,477	13,374	22,413	12,344
Northern Africa	30,616	50,949	43,111	55,066	46,436	53,249	45,037
Northern Europe	5440	10,551	6237	13,313	5178	11,187	4341
Southern Europe	67,523	60,360	49,848	97,449	61,084	67,485	54,855
Western Asia	36,863	48,303	35,667	44,772	32,175	44,414	31,731
Western Europe	19,298	25,981	15,209	72,795	35,716	74,182	41,736
Sum	181,202	214,028	162,305	313,187	196,560	278,016	193,006

the climate impact (model experiment 4) which leads to negative influences on crop yields and therefore to an increasing demand for irrigated area to fulfil the respective crop production goals. In both cases the "dry" climate scenario has a much stronger impact on the extent of irrigated area than the "wet" scenario. Note that the irrigated area under EcF without negative climate impacts already exceeds even the strongest increase under SuE with climate change. Moreover, the range of irrigated area change between the respective simulation runs is much larger for EcF (99.000 km^2) than for SuE (25.000 km^2) scenario input.

3.2. Irrigation water requirements

First we analyze the mean annual net irrigation water requirements for the "Baseline", as calculated in model experiment 1 (Fig. 4). Generally, a north-south-eastern gradient of increasing irrigation water requirements can be observed. Highest requirements are being modelled in the Egyptian Nile River basin, especially in the Nile River delta close to its inflow to the Mediterranean Sea, where average values of up to 1200 mm occur. The second most important irrigation hot spot is located in the Italian Po River basin with net irrigation water requirements of 115 mm per irrigated grid cell. Further hot spots can be identified in Turkey and Spain. Northern European countries, such as Denmark, Latvia and Lithuania generally need less irrigation water due to more suitable climatic conditions and crop choice but irrigated area can also reach large extents. It is important to note that gross irrigation water requirements are naturally higher than net irrigation water requirements, as water transport to the field, choice of irrigation technology, irrigation management, and different field sizes can drastically increase water demand (e.g. Wriedt et al., 2009b; Aus der Beek et al., 2010). Comparing the baseline total mean net irrigation water requirements for the pan-European regions, SE features with 16.15 billion m^3 the highest value, closely followed by NA with 15.6 billion m^3 and WA with 13.44 billion m^3 (Table 4). EEc can be found at the bottom of the table with 0.36 billion m^3, followed by NE with 0.47 billion m^3 and WE with 2.38 billion m^3 net irrigation water requirements.

In model experiment 2 we analyze the potential impact of climate change on future net irrigation water requirements. We conduct two simulation runs combining the irrigated area from the base map with climate forcing for the 2050s from the two aforementioned GCMs. The results from the simulation run using the "dry" climate scenario (IPCM4 GCM) show that total pan-European net irrigation requirements decrease by 1% to 53.06 billion m^3 (see Fig. 5c and Table 4). The largest regional deviation from this continental decrease can be found in two regions, which only hold a small share of total pan-European irrigation water requirements: EEc (+21%) and WE (+16%).

Results from the simulation run using the "wet" climate scenario (MIMR GCM) indicate that less water is needed for irrigation purposes. For entire pan-Europe the demand decreases by 5% to 51.23 billion m^3. Again, with +13% EEc shows the highest deviation from total net irrigation water requirements. However, in comparison with the simulation run using the "dry" climate scenario, contradicting trends can be observed for NE and WE that now also show a decrease in water requirements for irrigation.

Model experiment 3 portrays the effect of changing irrigated area on irrigation water requirements whereas climate data has been taken from the baseline period (1961–90). The first simulation run uses socio-economic drivers from the EcF scenario. For the whole of pan-Europe, net irrigation water requirements increase by 48% to 79.87 billion m^3 (Table 4), whereas regional differences in the magnitude of change dominate the picture. For example, on the one hand, in WA, NA, and EE increases of 25% to 35% are likely while on the other hand, NE and WE are facing increases between 157% and 253%. The main reason for these regional discrepancies can be attributed to the development of regional agricultural drivers (Section 2.2). The second simulation run (Fig. 5b) has been conducted with the socio-economic drivers from the "greener" SuE scenario. Here, pan-European net irrigation water requirements experience a small increase of 2% to 55.11 billion m^3. Again, regional differences dominate the picture, whereas in this scenario different directions of change occur. EE features the strongest decline with 30%, followed by SE (−11%), and WA (−7%). Three regions, EEc (+12%), NA (+25%), and WE (+69%) feature increases in net irrigation water requirements. A comparison of the results from the first two simulation runs illustrates that different socio-economic development pathways alone can cause a large difference in potential changes in future net irrigation requirements of nearly 25 billion m^3, which is almost 50% of current net irrigation water uses in pan-Europe.

As pointed out earlier, model experiment 4 consists of four simulation runs. The first simulation run was driven with the "dry" climate scenario (IPCM4) together with socio-economic input from the EcF scenario. From all simulation runs conducted in this study, it features with 78.06 billion m^3 the second largest increase in irrigation water requirements for pan-Europe (+45%). Furthermore, also four single pan-European regions show the largest increases throughout all eight scenarios. In WE net irrigation water requirements rise by 311%, in NE by 187%, in EEc by 145%, and in EEe by 49% (Fig. 5e, Table 4). The second simulation uses the "dry" climate scenario in combination with socio-economic input from the SuE scenario. Here, total pan-European net irrigation water requirements remain almost constant at 53.92 billion m^3 compared to the baseline. High regional increases can be observed in WE (+97%) and EEc (+37%), whereas decreases dominate in EEe (−23%) and SE (−14%) (Fig. 5f, Table 4). In the third simulation run the "wet" climate scenario (MIMR) has been combined with the EcF scenario. Total pan-European irrigation water requirements increase by 25% to 67.08 billion m^3. All regions, except SE, experience an increase in net irrigation water requirements, whereas WE (+264%), EEc (+188%), and NE (+134) feature the highest increases (Fig. 5g, Table 4). The fourth and last simulation run conducted as part of model experiment 4 connects the "wet" climate scenario with the SuE scenario. Even though two regions are expecting strong increases in net irrigation water requirements, WE (+103%) and EEc (+57%), total pan-European net irrigation water requirements decrease by 7% to 49.98 billion m^3, as these two regions only have a small share in total water requirements (see Fig. 5h and Table 4).

A comparison of the simulation runs from model experiments 2 and 3 on the pan-European level indicates that the impact of socio-economic changes is has a stronger influence on net irrigation water requirements than climate change (Table 4). Furthermore, also the

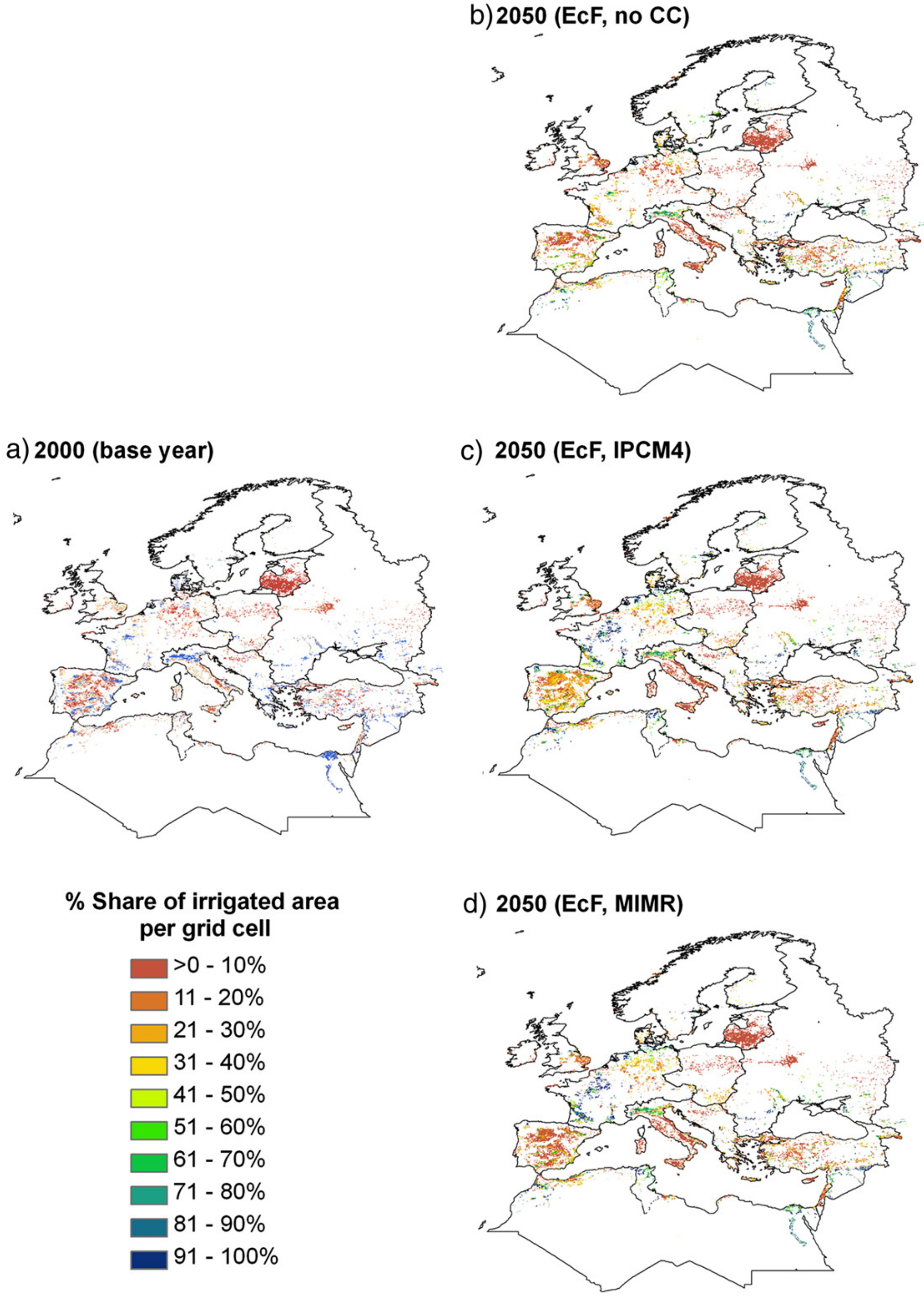

Fig. 3. Change in irrigated area between the years 2000 and 2050 for the Economy First scenario (EcF) in combination with different assumptions for climate change.

range between model outputs from both socio-economic scenarios is with nearly 25 billion m^3 much higher than between the two GCMs (1.8 billion m^3). This key finding is supported by the results from model experiment 4. A very illustrative example is the EcF scenario that without climate change and in combination with the “dry” IPCM4 climate yields the highest increases of irrigation water requirements of all scenarios (+45% and +48%), followed by its combination with the “wet” MIMR climate (+25%). As one would expect, the “green” SuE scenario in combination with climate from the MIMR GCM leads to the most favourable conditions and even a small decrease of 7% in future net irrigation water requirements.

4. Discussion and conclusion

This study examines and quantifies the future change of irrigated area in pan-Europe and the resulting effects on net irrigation water requirements. It provides new information required for the analysis of regional water stress where agriculture besides households and industrial water uses plays a crucial role (Alcamo et al., 2003). Moreover, the

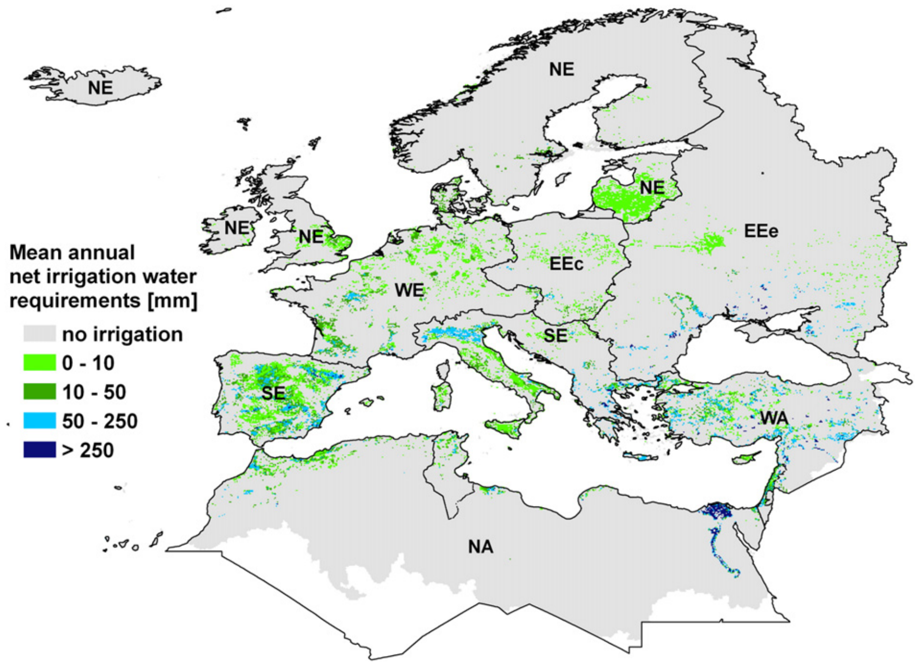

Fig. 4. Mean annual net irrigation requirements in [mm] for the baseline period (1961–90) as modeled with WaterGAP3 (EEc = Eastern Europe central, EEe = Eastern Europe east, NA = Northern Africa, NE = Northern Europe, SE = Southern Europe, WE = Western Europe, WA = Western Asia).

results might also contribute to further analysis of the impacts of irrigation and agricultural management intensity on regional meteorology (e.g. Douglas et al., 2009). For this particular purpose, our analysis should be expanded to account for rain-fed agriculture and other land-use types such as settlement or grazing land in order to give a more comprehensive view on regional land-use dynamics.

The main objective of our study was to analyze both the separate and combined effects of climate change and socio-economic changes on irrigated area and irrigation water requirements. The importance of these two factors already becomes obvious from the results for the baseline, driven with observed and reported data (experiment 1). Here, modelled net irrigation water requirements range from 0.36 billion m^3 in EEc to 16.15 billion m^3 in SE which can be attributed to the spatial heterogeneity of climate parameters such as temperature and precipitation (Mitchell and Jones, 2005) but also to agricultural management in terms of intensity and crop selection (Aus der Beek et al., 2011). Comparing the results from the scenario analysis (experiments 2 – 4) reveals that the impact of the socio-economic drivers on total pan-European net irrigation water requirements is higher than the impact of climate change. This effect is best illustrated by experiment 4 where the "dry" climate scenario in combination with the more sustainability oriented socio-economic scenario (SuE) causes almost no changes in irrigation water requirements, whereas in combination with the market oriented socio-economic scenario (EcF) it leads to an increase of 45%. These findings are in line with Arnell et al. (2004) and Alcamo et al. (2007) who identify socio-economic development as the key driver of water resource stresses with climate change being an additional impact factor which may worsen already existing problems.

It is important to note that the magnitude of the observed effect is strongly determined by the applied scenario methodology. While climate change scenarios that are generated with GCMs are based on physical principles, the degrees of freedom being involved in the participatory development of plausible socio-economic scenarios (see Section 2.2) are very wide and often aim at exploring very diverse potential development pathways. A good example are the scenario inherent assumptions about the future development of crop yields due to technological change which play a crucial role for the expansion of irrigated cropland. In this aspect the SCENES scenarios portray the different views from scientific literature to which degree future yield increases can be realized or whether biophysical and/or socio-economic limitations will hinder further developments in crop breeding (e.g. Jaggard et al., 2010; Foley et al., 2011). In particular the results from the SuE scenario illustrate that strong agricultural intensification might help to substantially reduce the demand for agricultural land (in our case irrigated area) and therefore might open new opportunities to re-establish natural ecosystems on set-aside land. Here, it should be

Table 4
Modeled mean net irrigation water requirements in billion m^3 under the IPCC-SRES scenario A2 with two GCMs (IPCM4 and MIMR) for 2040 – 2069 and two socio-economic scenarios (EcF and SuE). Numbers in parenthesis describe relative changes compared to the baseline (1961 – 1990), expressed in percent.

Model experiment	1	2		3		4			
Climate forcing	Base 61–90	IPCM4 2050	MIMR 2050	Base 61–90	Base 61–90	IPCM4 2050	IPCM4 2050	MIMR 2050	MIMR 2050
Land use	Base 2000	Base 2000	Base 2000	EcF 2050	SuE 2050	EcF 2050	SuE 2050	EcF 2050	SuE 2050
Eastern Europe (central)	0.36	0.43 (+21)	0.41 (+13)	0.72 (+101)	0.40 (+12)	0.88 (+145)	0.49 (+37)	1.04 (+188)	0.56 (+57)
Eastern Europe (eastern)	5.47	5.93 (+8)	5.91 (+8)	7.39 (+35)	3.81 (−30)	8.12 (+49)	4.20 (−23)	7.32 (+34)	3.77 (−31)
Northern Africa	15.60	15.17 (−3)	14.35 (−8)	21.01 (+35)	19.48 (+25)	19.63 (+26)	18.41 (+18)	18.64 (+19)	17.40 (+12)
Northern Europe	0.47	0.49 (+5)	0.46 (−2)	1.20 (+157)	0.46 (−2)	1.34 (+187)	0.51 (+8)	1.09 (+134)	0.40 (−15)
Southern Europe	16.15	15.68 (−3)	14.90 (−8)	24.35 (+51)	14.43 (−11)	22.77 (+41)	13.97 (−14)	14.91 (−8)	11.49 (−29)
Western Asia	13.44	12.59 (−6)	12.83 (−9)	16.79 (+25)	12.50 (−7)	15.53 (+16)	11.66 (−13)	15.40 (+15)	11.53 (−14)
Western Europe	2.38	2.77 (+16)	2.37 (−0)	8.42 (+253)	4.03 (+69)	9.79 (+311)	4.69 (+97)	8.67 (+264)	4.82 (+103)
SUM	53.87	53.06 (−1)	51.23 (−5)	79.87 (+48)	55.11 (+2)	78.06 (+45)	53.92 (−0)	67.08 (+25)	49.98 (−7)

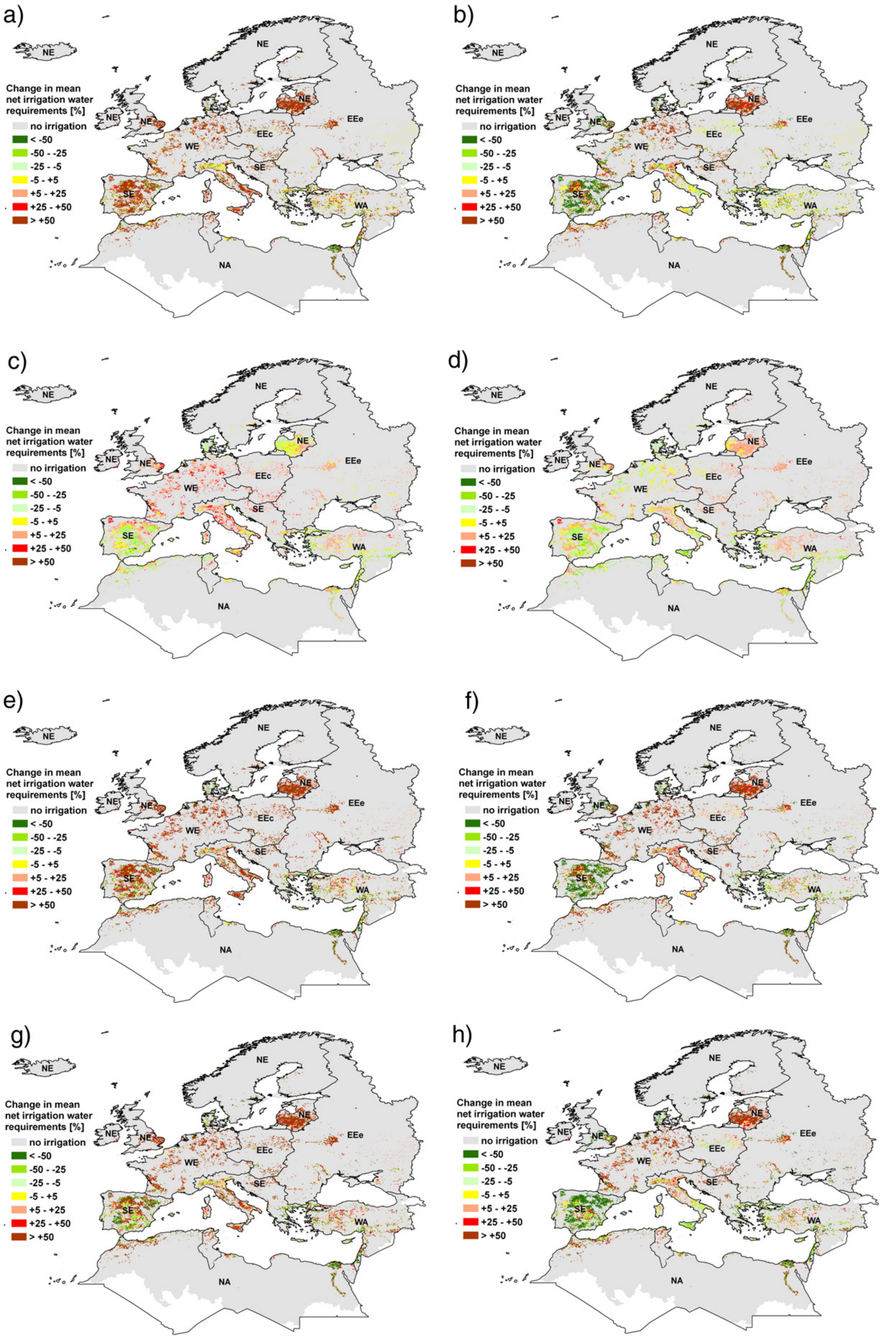

Fig. 5. Change in mean annual net irrigation requirements compared to baseline (1961–1990) for different combinations of climate change (CLIM) and socio-economic (SEC) scenarios. a) CLIM: baseline, SEC: EcF; b) CLIM: baseline, SEC: SuE; c) CLIM: IPCM4, SEC: baseline; d) CLIM: MIMR, SEC: baseline; e) CLIM: IPCM4, SEC: EcF; f) CLIM: IPCM4, SEC: SuE; g) CLIM: MIMR, SEC: EcF; h) CLIM: MIMR, SEC: SuE.

an important goal for agricultural and environmental policies to find trade-offs between these benefits and negative consequences of the over-use of fertilizers and pesticides for example on nutrient leaching and farmland biodiversity (e.g. Ewers et al., 2009).

Beside the overall socio-economic boundary conditions, another important aspect that will determine future agricultural development is the capability of farmers to adapt their crop production systems to the changing temperature and precipitation regimes. Before this background Falkenmark and Rockström (2006) have identified different strategies for increasing the water use efficiency in agriculture, aiming at a higher "crop per drop" ratio. Approaches to increase the efficiency of irrigation systems and to minimize water losses, e.g. by using advanced technologies such as drip irrigation are beyond the system boundaries of our analysis, as we concentrate on quantifying net crop irrigation water requirements which are equal to the evapotranspiration flux. A decrease of evapotranspiration can be achieved by soil preparation (e.g. mulching) or by adaptation of crop selection (e.g. drought tolerant varieties) and management. In our study we pick up the last point by implementing an irrigation model that takes into account climate data of the entire year and computes the most suitable crop-specific growing period for each raster cell within pan-Europe. This adaptive cropping calendar emulates crop sowing date decisions from local farmers who automatically readjust to a changing environment based on their experience (Döll, 2002). Therefore, the decreases in net irrigation demand within climate change driven scenarios both characterized by significantly increasing air temperatures can be explained by changing crop sowing dates. As an example, Fig. 6 shows the change in crop sowing month between the baseline and the climate change scenario from IPCM4 for the Iberian Peninsula. It becomes evident that in most parts of that region the cropping period starts one to two months earlier, as due to air temperature increases climatic conditions are already suitable for sowing, and high irrigation demands in July and August can be avoided. Sowing days can also be delayed into late summer, as less frost days are occurring in November and December due to the climate change induced air temperature increase as modelled with IPCM4.

To test the adaptive cropping calendar of the model and to analyze the effects of climate change on net irrigation requirements with a fixed cropping calendar, an additional simulation run for the 2050s with climate input from the IPCM4 GCM and socio-economic data for the baseline (identically with column 2 in Table 4) has been conducted with non-adapted sowing dates from the baseline period. Here, pan-European net irrigation water requirements increase by 15% from 53.87 to 61.85 billion m^3. As shown earlier, the same model run with the adaptive cropping calendar yielded a net irrigation demand decrease of 1% to 53.06 billion m^3 (Table 4). With these results we can illustrate that with adaptation measures, such as moving sowing days, local farmers are able to mitigate the impact of climate change on local water resources especially in already water scarce arid and semi-arid regions (see also Thomas, 2008). When considering the whole of pan-Europe, the adjustment of the sowing dates saved about 9 billion m^3, which is nearly 17% of today's net irrigation water abstractions.

For better interpretation of the outcomes of this study we also have to discuss the caveats and uncertainties involved in the modelling methods and data. Regarding the modelling methods, the functionality and results of the WaterGAP3 irrigation model have been verified and validated by Aus der Beek et al. (2010). Possible improvements of the algorithm include the adjustment of the cropping period for each crop type individually, which is currently fixed at 150 days. Furthermore, the duration of the growing period should be regionalized as well, as it differs within climate regions. Contrary, an evaluation of the model for calculating the expansion of irrigated area was not possible because a map or real irrigated area existed for only one point in time. As we have implemented a very robust downscaling routine (area increase in proportion to existing irrigated area) the model delivers plausible results under the tested scenario conditions. Possible improvements of the modelling technique also include the implementation of adaptation mechanisms regarding crop selection and the fraction of irrigated crop production which is currently left constant at baseline level during the scenario runs.

Furthermore it is important to note that our study focuses on changes in long term mean values of irrigation water requirements. As these values are based on the output of the WaterGAP3 irrigation model that operates with a temporal resolution of 1 day, it would be possible to use this model also to account for the day-to-day variability of climate factors. This, according to Thomas (2008) would be an essential prerequisite for obtaining "more realistic" results and to assess for example the effects of heat waves and droughts on irrigation water

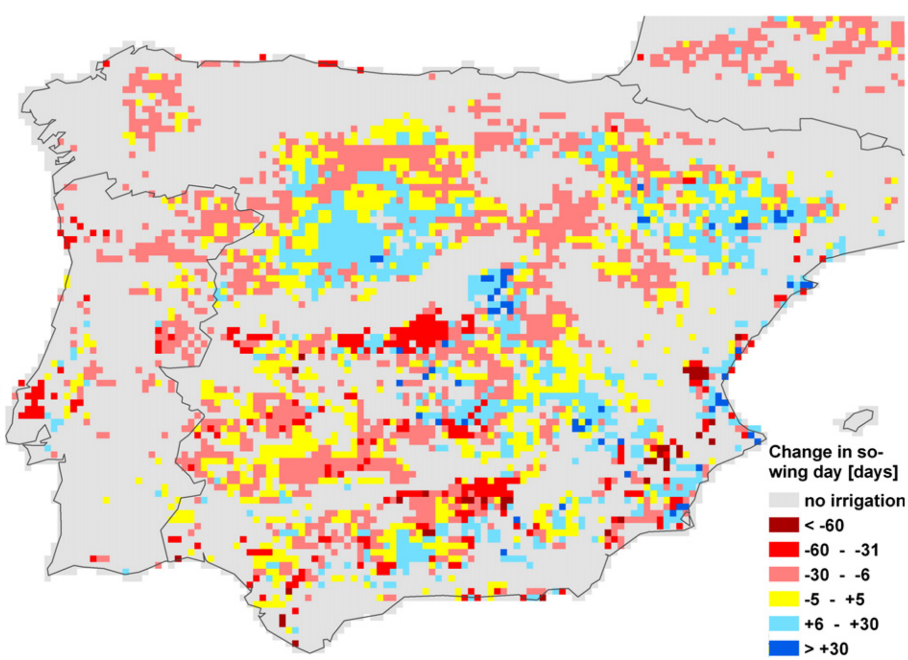

Fig. 6. Comparison of change in mean sowing day for the 2050s (IPCM4) to baseline (1961–90) for the Iberian Peninsula.

requirements (Van der Velde et al., 2010). Nevertheless this type of study would require either daily weather data (measured or from GCM output) or a more sophisticated method to temporally downscale the monthly data than the approach that is currently applied.

As pointed out earlier, major sources of uncertainty of the input data are the assumptions about future socio-economic and climatic developments. Here scenario analysis provides a suitable tool to identify and to analyze a wide range of plausible future development pathways. An overview of uncertainties in GCM climate projections is presented in IPCC (2007). We have decided to use only two characteristic climate simulations representing "wet" and "dry" future conditions within the SRES A2 scenario setting for our analysis. This decision was motivated by the demands of the scenario building process (Section 2.2). One way to further improve our study design in this respect would be the use of ensemble climate data as demonstrated for instance by Challinor et al. (2005), which would allow to carry out our study in a probabilistic framework. Moreover, the climate scenarios were generated with a delta change approach which does not drastically change future year-to-year variability of climate parameters. The use of bias corrected GCM data might help to give a better picture of future impacts on changing climate variability on irrigation water requirements. Together with using daily weather data (see above) this would enable further studies to analyze how farmers can use irrigation as a management tool not only to adapt to changing climate trends but also to weather extremes (Van der Velde et al., 2010). In this context also the competition of agriculture with other sectors, e.g. electricity production (Flörke et al., 2011), for available water resources should be taken into account to identify problems and limitations of adaptation.

In conclusion, we could demonstrate how our newly developed model approach facilitates the analysis of current and future impacts of socio-economic development and climate change on the net irrigation water requirements in pan-Europe. The methodology has been tested with good results in a set of model experiments where the respective influences could be quantified and evaluated. Moreover, we have identified ways to improve the modelling framework and to address uncertainties within climate data in future studies. Important messages from our model experiments are that agricultural intensification plays a key role to reduce the area demand for irrigated cropland and that adaptation to changing climate conditions can help to substantially increase water use efficiency in irrigated crop production. Therefore these two processes are essential to sustain future food production for a still growing world population.

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