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Mediterranean irrigation under climate change: more efficient irrigation needed to compensate increases in irrigation water requirements

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Abstract

Irrigation in the Mediterranean is of vital importance for food security, employment and economic development. This study systematically assesses how climate change and increases in atmospheric CO_2 concentrations may affect irrigation requirements in the Mediterranean region by 2080–2090. Future demographic change and technological improvements in irrigation systems are accounted for, as is the spread of climate forcing, warming levels and potential realization of the CO_2-fertilization effect. Vegetation growth, phenology, agricultural production and irrigation water requirements and withdrawal were simulated with the process-based ecohydrological and agro-ecosystem model LPJmL after a large development that comprised the improved representation of Mediterranean crops. At present the Mediterranean region could save 35 % of water by implementing more efficient irrigation and conveyance systems. Some countries like Syria, Egypt and Turkey have higher saving potentials than others. Currently some crops, especially sugar cane and agricultural trees, consume in average more irrigation water per hectare than annual crops. Different crops show different magnitude of changes in net irrigation requirements due to climate change, being the increases most pronounced in agricultural trees. The Mediterranean area as a whole might face an increase in gross irrigation requirements between 4 and 18 % from climate change alone if irrigation systems and conveyance are not improved (2 °C global warming combined with full CO_2-fertilization effect, and 5 °C global warming combined with no CO_2-fertilization effect, respectively). Population growth increases these numbers to 22 and 74 %, respectively, affecting mainly the Southern and Eastern Mediterranean. However, improved irrigation technologies and conveyance systems have large water saving potentials, especially in the Eastern Mediterranean, and may be able to compensate to some degree the increases due to climate change and population growth. Both subregions would need around 35 % more water than today if they could afford some degree of modernization of irrigation and conveyance systems and benefit from the CO_2-fertilization effect. Nevertheless, water scarcity might pose further challenges to

the agricultural sector: Algeria, Libya, Israel, Jordan, Lebanon, Syria, Serbia, Morocco, Tunisia and Spain have a high risk of not being able to sustainably meet future irrigation water requirements in some scenarios. The results presented in this study point to the necessity of performing further research on climate-friendly agro-ecosystems in order to assess, on the one side, their degree of resilience to climate shocks, and on the other side, their adaptation potential when confronted with higher temperatures and changes in water availability.

1 Introduction

Water is a scarce resource in the Mediterranean region, not only in absolute terms, but also through the concentration of precipitation in the winter months and the high interannual variability with the presence of frequent droughts (Lionello et al., 2006). Climate change is expected to exacerbate this situation by increasing potential evapotranspiration, decreasing rainfall and increasing the frequency and intensity of droughts (Niang et al., 2014; IPCC, 2014). For example Vautard et al. (2014) calculated precipitation decreases reaching 20 % for 2 °C global warming and states that Southern Europe is likely to experience higher warming than the global average, especially in summer. Additionally, minimum river flows in Southern Europe may be lowered up to 40 % by the middle of the century and streamflow drought conditions might continue to be intensified by human water consumption, especially due to irrigation (Forzieri et al., 2014).

Climate change is not the only factor affecting water supply and demand, population and economic growth in the southern shores of the Mediterranean and urbanization in the entire Mediterranean region will very likely further increase water extractions. Urban population in Northern Africa and Southern Europe is expected to increase, from 51 to 63 % and from 70 to 80 %, respectively (United Nations, 2014), leading to more water-consuming diets, higher water demand for energy production and changes in hygiene behaviour. Additional pressure on water resources may come in the Southern shores through increased water use for new industries and in the Northern shores due to expansion of biofuel plantations (the EU has the objective of supplying 10 % of transport fuel with biofuels by 2020, EU, 2007). Moreover, expansion of tourism is expected to increase water demand, especially in the dry period (Lanquar, 2013).

The combination of these factors will very likely strengthen the debate on the allocation on water resources between the different economic sectors and intensify the requirements of increasing the water use efficiency in all of them. The agricultural sector of the Mediterranean might be strongly affected by this debate since agriculture is the sector that contributes the most to water withdrawal. In average, around 50 % of total water withdrawal in the Mediterranean is for agriculture, with strong sub-regional patterns, from around 1.3 % in Croatia, 12 % in France up to almost 90 % in Syria, Egypt, Cyprus and Greece (FAO, 2015). And these proportions are expected to further increase in future, especially in the developing sub-regions (Faurès et al., 2000). Further complexity is added to these issues by the fact that there are environmental concerns linked to irrigated agriculture, including groundwater overexploitation and negative consequences of unsustainable management, such as salinization (Soussi et al., 2013). However, deallocating water resources from the agricultural sector would affect food security, the economy and the environment. For example, irrigated agriculture contributes 28 % of GDP in Syria and produce ~ USD 33.7 billion in Spain (Rodríguez-Díaz and Topcu, 2010; Manero, 2008), employs 400 000 people in Southern France (AIRMF, 2009) and provides ecosystem services, such as landscape preservation and biodiversity conservation (Nieto-Romero et al., 2014).

All this delivers the certainty that irrigated agriculture will be at the core of the future discussion on allocation of water resources. And coping with this situation without damaging the agricultural sector and while providing the water needed by the other sectors will require informed discussions and decisions based on quantitative assessments. Those quantifications, necessarily, will have to include estimations about the present and future water requirements for irrigated agriculture as well as the water saving potentials in this sector. However, only few comprehensive studies have been made on estimations of future irrigation requirements until present, as revised in the following paragraph.

Döll and Siebert (2002) were probably the first ones quantifying irrigation water requirements at the global level. They distinguished two crop classes (rice and non-rice), analysed at 2 global climate models (GCMs) and pointed out the effect of higher climate variability on future irrigation requirement. In a later study, Siebert et al. (2010) computed irrigation consumptive water use by means of the GCWM model for the present time. Using the FAO's agro-ecological zones model, Fischer et al. (2007) presented estimations of future irrigation water requirements under mitigated and unmitigated climate change for different regions, including Western Europe and the Middle East and North Africa. They came to the conclusion that the Middle East and North Africa may be affected by a high water scarcity in 2080, indicating potential difficulties for meeting future irrigation water requirements. They also indicated that mitigation of climate change would reduce increases in irrigation requirements, being the effect in Europe larger than in Northern Africa. Konzmann et al. (2013) presented simulated future irrigation requirements globally for around 10 crop functional types under 19 GCMs with a former version of the LPJmL model, and came to the conclusion that the Mediterranean region may need more water under climate change. Souissi et al. (2013) compiled data from various sources, showing estimates of irrigation water use of 181 $\mathrm{km^3\,yr^{-1}}$ in 2005 for the Mediterranean region. For 2025, they show a range of 157 to 212 $\mathrm{km^3}$, depending on the scenario (business as usual or sustainable development in relation to water resources policies), pointing to possible savings in irrigation water but also to potential increases in irrigation water requirements. Elliot et al. (2013) pointed to the risk of increasing irrigation water requirements under climate change in some regions, including the Mediterranean. These conclusions are complemented by a number of local-scale studies, focused on a reduced number of crops, for example Teyssier (2006) for the Midi-Pyrénées region in France and Rodríguez-Díaz et al. (2007) for the Guadalquivir river basin in Spain. The literature review shows some common elements, indicating that the Mediterranean region may suffer in future from a combination of increased water scarcity and higher water demand.

The present study aims to advance substantially the present research status by accounting, in a comprehensive framework, for several previously unconsidered variables: climate change impacts on irrigation water requirements in the Mediterranean region are simulated with a newly developed version of the LPJmL model that considers 88 % of irrigated areas and represents the special structure of Mediterranean agriculture, which is dominated by perennial crops (Fader et al., 2015). The simulations are performed for 4 warming levels and 19 GCMs. LPJmL (Sitch et al., 2003; Bondeau et al., 2007; Gerten el al., 2004; Schapfhof et al., 2013) is a mechanistic hydrology and agro-ecosystem model that has important features for the quantification of irrigation requirements, such as a dynamic coupling of water, agricultural production and plant physiology, and the consideration of changes in phenology through to dynamic growing periods, sowing dates and flowering times. Additionally, we consider in this study the link between demographic change and water demand as well as the possibility of improving irrigation and conveyance systems in future by adopting water saving technologies and infrastructure.

One of the largest uncertainties in climate change impact research related to vegetation is the effect of higher CO_2 concentrations in the atmosphere on plant growth, phenology, water requirements and production. In general higher CO_2 in the atmosphere has the potential to increase photosynthesis and water productivity of plants, especially the ones with C3 photosynthetic pathways (Hatfield et al., 2011; Ackerman and Stanton, 2013). This is why this effect has been called "CO_2-fertilization effect". Nevertheless, the environmental and genotype dependences, consequences of co-limitations (especially nutrients and water) as well as the order of magnitude and changes in nutritional values are still uncertain (Porter et al., 2014; DaMatta et al., 2010). For example, DaMatta et al. (2010) revised literature and came to the conclusion that the beneficial effect of CO_2 could be offset by higher temperatures and altered precipitation patterns. FACE-experiments, enclosure studies measurements and modelling efforts have tried and are trying to shed light on this issue but have not given consistent results until now (Long et al., 2006; Tubiello et al., 2007; Ainsworth et al., 2008). Modelling experiments usually deal with this uncertainty by making two sets of simulations, one using as inputs dynamic CO_2 concentrations in the atmosphere, and one with constant CO_2 concentrations. The responses of vegetation will very likely fall in the range of these two extremes, and in order to assess this in-between-space in more detail, we account additionally for one more scenario that takes a “reduced” CO_2-fertilization effect.

Hence, this study aims to answer following research questions:

1. How much irrigation water do we need today in the Mediterranean region? What are the most water-intensive crops?
2. What countries have potentials for saving water through changes in the irrigation and conveyance systems?
3. How do different levels of climate change impact future irrigation requirements? And are there sub-regional patterns (East, South, North)?
4. Are different crops affected differently by climate change?
5. What is the potential role of demographic change and water scarcity?

Section 2 gives an overview of the methodology of the study, including model functioning, CO_2-fertilization scenarios and scenarios of improvements in irrigation technologies. Section 3 presents the results for the present irrigation requirements and changes under climate, demographic and technological change. Section 4 offers possible implications and discusses prospects for further research.

2 Methods

Vegetation growth, phenology, agricultural production and irrigation water requirements and withdrawal were simulated with the process-based agro-ecosystem and hydrology model LPJmL (Sitch et al., 2003; Bondeau et al., 2007; Rost et al., 2008; Gerten et al., 2004; Schapfhof et al., 2013). LPJmL was recently developed for the inclusion of Mediterranean crops by Fader et al. (2015), which delivered a model that considers 88 % of irrigated areas divided in 12 annual crops (temperate cereals, rice, tropical cereals, maize, temperate roots, tropical roots, pulses, rapeseed, soybeans, sunflower, sugar cane, potatoes), 7 perennial crops (nut trees, date palms, citrus trees, orchards, olive trees, grapes, cotton) and 4 groups parameterised as herbaceous crops (fodder grass, vegetables, management grasslands, "other crops").

Annual crops grow and are harvested according to the heat unit theory and agricultural trees are implemented as evergreen or summer green trees where the fruits are represented by a plant-specific portion of NPP. Vegetables and fodder grasses are parametrised as C3 grass, managed grasslands as a mixture of C3 and C4 grasses (see Bondeau et al. (2007) and Fader et al. (2015) for more details). Management is calibrated to best match FAO yields (FAOSTAT, 2014), both for annual and perennial crops. This routine represents differences in management intensity (see Fader et al. (2010, 2015) for more details).

Model inputs consist in climate variables and global CO_2 concentrations (see below), soil texture as described in Schaphoff et al. (2013), and a dataset of land use patterns compiled from different sources as explained in Fader et al. (2015) (see Fig. S1 in the Supplement for crop-specific areas in the Mediterranean region).

Climate data for the present and past time was taken from CRU 3.10. For the climate change simulations, the PanClim dataset from Heinke et al. (2013) were used. They performed pattern downscaling of GCM data using global mean temperature and greenhouse gas trajectories from a reduced complexity climate model (MAGICC6, Meinshausen et al., 2011) to derive climate scenarios covering warming levels from 2 to 5° above pre-industrial levels around the year 2100.

We account for the effect of higher CO_2-concentrations in the atmosphere by analysing three scenarios:

- Dynamic CO_2 (DYN): LPJmL runs with the corresponding global CO_2 concentrations (from the MAGICC6 model, see Heinke et al., 2013) in accordance with each warming level. DYN assumes full CO_2-fertilization effect and no limitation of this effect through lack of other resources (most notably soil nutrients).
- Reduced CO_2 (RED): this scenario assumes that the CO_2-fertilization effect will occur but for higher warming levels, less strongly than in DYN. Technically we implemented this using the CO_2 concentration values of 1 lower warming level. For example, the CO_2 concentrations of 4° warming DYN are the same than the 5° warming RED, but the climate forcing is different.
- Constant CO_2 (CONST): this scenario assumes that plants will not benefit from CO_2-fertilization due to management deficiencies, lack of resources, climatic stress and higher frequency of extreme events. Technically we implement this by keeping CO_2 concentrations constant to the level of 2009 (387.85 ppm), while varying climate forcing according to the different warming levels.

The CO_2 concentrations trajectories for every of these scenarios are plotted in Fig. S2.

2.1 Irrigation water requirements, water withdrawal and transformation of irrigation systems

Irrigation in LPJmL is triggered in irrigated areas when soil water content is lower than 90 % of field capacity in the upper 50 cm of the soil. Plants' net irrigation water requirements (NIR) is modelled as the amount of water that plants need, taking into account the relative soil moisture and the water holding capacity of the irrigated layer:

$$\mathrm{NIR}\left[\mathrm{mm\,d^{-1}}\right] = \min\left(\frac{1}{f_{\mathrm{Ril}}}\left(\frac{D}{\mathrm{Sy}} - w_{\mathrm{r}}\right), 1 - w_{\mathrm{il}}\right)\mathrm{WHC} \quad (1)$$

where D [mm d^{-1}] is the atmospheric demand, which depends on potential evapotranspiration and canopy conductance. Sy [mm d^{-1}] is the soil water supply, which equals to a crop's specific maximum transpirational rate if the soil is saturated or declines linearly with soil moisture. f_{Ril} is the proportion of roots in the irrigated layer. w_{il} is the water content in the irrigated layer. w_{r} is the water content weighted with the root density for the soil column. WHC [mm] is the field capacity of the irrigated layer (water holding capacity).

Water withdrawal or extraction, also called gross irrigation water requirements (GIR), is obtained by dividing NIR by the project efficiencies (EP):

$$\mathrm{GIR}\left[\mathrm{mm\,d^{-1}}\right] = \frac{\mathrm{NIR}}{\mathrm{EP}} \tag{2}$$

EP is a country-specific parameter calculated by Rohwer et al. (2006) taking into account reported data on conveyance efficiency (EC), field application efficiency (EA) and a management factor of the irrigation system (MF):

$$\mathrm{EP}\ [0\,\mathrm{to} < 1] = \mathrm{EC}\cdot\mathrm{EA}\cdot\mathrm{MF} \tag{3}$$

EA represents the water use efficiency on the fields and increases from surface irrigation systems, over mixed (sprinkler and surface systems) and pure sprinkler system, to drip irrigation systems. EC represents the water use efficiency in the distribution/conveyance systems belonging usually to farmer associations and is assumed to be linked to irrigation systems. Thus, EC is smaller for surface irrigation systems (assumed to be supplied with open canals) than for sprinkler and drip irrigation systems, which are assumed to be supplied with pressurized pipelines. MF varies between 0.9 and 1 and is higher in pressurized and small scale systems under the assumption that large-scale systems are more difficult to manage and, thus, prone to have slightly lower efficiency in water use, especially when surface irrigation is at play (see values in Table 1 and more details in Rohwer et al., 2006).

In order to test the potentials for water savings through more efficient irrigation and conveyance systems, we assume in addition to the status quo regarding irrigation efficiencies as explained above, two more scenarios with improvements in irrigation systems and water conveyance infrastructures:

- Improvement scenario (IMP): adoption of more water-efficient irrigation and conveyance systems. In this scenario it is assumed that one level of improvement in irrigation systems is achieved in every country of the region (as shown in Table 1). Technically, we implemented that in a set of climate change runs with changed EP parameters, assuming a higher efficiency in irrigation and conveyance systems (see Eq. (3) and Table 1).

- Most-efficient scenario (DRIP): in this scenario it is assumed that all countries of the region implement drip irrigation systems combined with water conveyance through pipelines.

- Standard scenario (STD): this scenario represents the business as usual possibility, where irrigation and conveyance systems remain as they are in present time.

2.2 Simulation protocol and descriptive statistics

Three simulations (STD, IMP, DRIP) were performed for the present time and analysed as means over the years 2000 to 2009.

684 simulations were performed for the future: 19 GCMs, 4 warming levels (from 2 to 5° in 1 °C steps), 3 CO_2-fertilization scenarios (DYN, CONST, RED), 3 irrigation scenarios (IMP, DRIP, STD). Results are evaluated for the period 2080 to 2090 as medians or means as explained in the following equations.

Regions and sub-regions medians and simple means over GCMs were computed as last steps after averaging over years, and aggregation over grid-cells and crops as follows:

$$\mathrm{NIR}_{80\text{–}90,\mathrm{GCMx}}\left[\mathrm{km}^3\right] = \frac{\sum\limits_{P=1}^{n}\sum\limits_{\mathrm{cr}=1}^{n}\left(\left(\sum\limits_{Y=1}^{n}\mathrm{NIR}_{Y,P,\mathrm{cr}}\cdot 10\cdot \mathrm{area}_{Y,P,\mathrm{cr}}\right)\Big/ nY\right)}{10^9} \qquad (4)$$

where $\mathrm{NIR}_{Y,P,\mathrm{cr}}$ [$\mathrm{mm\,d^{-1}}$] is the net irrigation requirement of a crop cr, for year Y, in a grid-cell P, according to one GCM (GCMx). Area [hectares] is the irrigated area covered in P by the crop cr. nY is the number of years for the period evaluated (11 for 2080 to 2090). 10 converts from mm to $\mathrm{m^3\,ha^{-1}}$, and 10^9 from $\mathrm{m^3}$ to $\mathrm{km^3}$.

Spatial explicit changes in variables are computed for each scenario and GCM separately as:

$$\mathrm{NIR\_Change}_P\,[\%] = \frac{\mathrm{NIR}_{80\text{–}90,\mathrm{GCMx},P}}{\mathrm{NIR}_{00\text{–}09,P}} \cdot 100 - 100. \tag{5}$$

Thus, negative (positive) values represent decreases (increases).

2.3 Influence of demographic change

Once calculated all combinations of irrigation scenarios, $\mathrm{CO_2}$-fertilization effect and warming scenarios the influence of demographic change was accounted for as follows:

$$\mathrm{GIR}_{\mathrm{Pop},80\text{–}90,\mathrm{IRR},\mathrm{WAR},\mathrm{CO2}}\left[\mathrm{km^3}\right] = \mathrm{GIR}_{80\text{–}90,\mathrm{IRR},\mathrm{WAR},\mathrm{CO2}} + \frac{\left(\left(\frac{\mathrm{POP}_{80\text{–}90}}{\mathrm{POP}_{00\text{–}09}} - \frac{\mathrm{PROD}_{80\text{–}09,\mathrm{IRR},\mathrm{WAR},\mathrm{CO2}}}{\mathrm{PROD}_{00\text{–}09}}\right) \cdot \mathrm{PROD}_{00\text{–}09} \cdot \mathrm{VWC}_{80\text{–}90,\mathrm{IRR},\mathrm{WAR},\mathrm{CO2}}\right)}{10^{-9}} \tag{6}$$

where $\mathrm{GIR}_{\mathrm{Pop},80\text{–}90,\mathrm{IRR},\mathrm{WAR},\mathrm{CO2}}$ [$\mathrm{km^3}$] are the gross irrigation requirements, as average over the period of time 2080–2090, adjusted for population growth (POP) for the irrigation scenario IRR (STD, IMP, DRIP), the warming level WAR and the $\mathrm{CO_2}$-fertilization scenario CO2 (DYN, CONST, RED). $\mathrm{GIR}_{80\text{–}90,\mathrm{IRR},\mathrm{WAR},\mathrm{CO2}}$ [$\mathrm{km^3}$] are the gross irrigation requirements as computed in every combination of IRR, WAR and CO2 without influence of demographic change. POP [hab] are the population numbers from the Medium Fertility scenario from United Nations (2013). PROD [t] is the irrigated production of agricultural goods. VWC [$\mathrm{m^3\,t^{-1}}$] is the virtual water content of irrigated agricultural products calculated as the division of gross irrigation requirements divided by production. GIR, PROD and VWC are medians over the 19 GCM runs; 10^{-9} converts from m^3 to km^3.

This computation accounts for production gains/losses through different levels of climate change and CO_2-fertilization as well as the changes in the productivity of irrigation water (i.e. changes in VWC). The output of this approach assumes that population change will linearly decrease/increase food demand and sheds light on future irrigation requirements in case of (a) no future increases in import dependency by increases of virtual water imports, (b) unchanged diets, and (c) unchanged proportions of irrigated to rainfed areas in case of agricultural expansion and no changes in agricultural management besides the ones linked to modernization of irrigation systems.

2.4 Influence of water scarcity

A quantification of water scarcity for future irrigation requirements was carried out by comparing the simulated irrigation water requirements under climate (with and without demographic change) with 4 water availability scenarios. These renewable water availability scenarios (RWA) were calculated on the basis of AQUASTAT data for the current time at national level (FAO, 2015). They differ in the external inflows considered as well as in the consideration or not of environmental flow requirements.

For the "politically assured, sustainable scenario" (POL_SUS) we only consider the external inflow secured through treaties at present and exclude water needed by aquatic ecosystems. Thus, the calculation is:

$$\begin{aligned}\mathrm{RWA}_{\mathrm{POL\_SUS}}\left[\mathrm{km}^3\right] &= \mathrm{RWR}_{\mathrm{I,S+G}} + \mathrm{Inflow}_{\mathrm{E,S,T}} - \mathrm{Outflow}_{\mathrm{E,S,T}} + \mathrm{Inflow}_{\mathrm{E,G}} - \mathrm{Outflow}_{\mathrm{E,G}} \\ &+ \mathrm{BorderRWR}_{\mathrm{Lakes+Rivers}} - \mathrm{WU}_{\mathrm{municipal}} - \mathrm{WU}_{\mathrm{industry}} - \mathrm{EF}_{\mathrm{S}} - \mathrm{V}_{\mathrm{S+G}} \qquad (7)\end{aligned}$$

where RWA is the renewable water availability in the "politically assured, sustainable scenario". $\mathrm{RWR}_{\mathrm{I,S+G}}$ represents the renewable water resources as sum of the internally (I) produced surface (S) and groundwater (G). Double counting is avoided by

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

considering the overlap variable of AQUASTAT. $\text{Outflow}_{\text{E,S,T}}$ and $\text{Inflow}_{\text{E,S,T}}$ is the surface water outflow and inflow from/to other countries, respectively, secured through treaties (T). $\text{Inflow}_{\text{E,G}}$ and $\text{Outflow}_{\text{E,G}}$ is the groundwater entering and leaving the country. $\text{BorderRWR}_{\text{Lakes+Rivers}}$ is the to the country corresponding part of border lakes and rivers. WU_{X} is the water withdrawal for industry and municipal use. EF_{S} is equal to 30 % of internally produced $\text{RWR}_{\text{I,S}}$ and represents the water needed for conservation of aquatic ecosystems, an assumption widely used in the hydrological community.

V is equal to 30 % of internally produced $\text{RWR}_{\text{I,S+G}}$ and represents the amount of water that is unavailable due to technical difficulties, lack of infrastructure, temporal variability and mismatching of temporal availability and spatial needs.

In the second "given, sustainable scenario" (GIV_SUS) we additionally account for external inflows not submitted to treaties ($\text{Inflow}_{\text{E,S,noT}}$):

$$\text{RWA}_{\text{GIV\_SUS}}\left[\text{km}^3\right] = \text{RWR}_{\text{I,S+G}} + \text{Inflow}_{\text{E,S,T}} + \text{Inflow}_{\text{E,S,noT}} - \text{Outflow}_{\text{E,S,T}} + \text{Inflow}_{\text{E,G}} - \text{Outflow}_{\text{E,G}} + \text{BorderRWR}_{\text{Lakes+Rivers}} - \text{WU}_{\text{municipal}} - \text{WU}_{\text{industry}} - \text{EF}_{\text{S}} - \text{V}_{\text{S+G}}. \tag{8}$$

Avoiding the consideration of environmental flow requirements in the equations 7 and 8, yield the "politically assured, unsustainable scenario" (POL_UNSUS) and the "given, unsustainable scenario" (GIV_UNSUS), respectively.

AQUASTAT data are for the present time and thus, they do not consider changes in water availability due to climate change and increases of water demands through other sectors.

Maximal and median GIR under climate change, with and without the influence of population change and transformation of irrigation systems, are compared to these scenarios for the period of time 2080–2090.

3 Results

3.1 Mediterranean region could save 35 % of water at present

Figure 1 shows patterns of GIR in absolute terms for the present time. Irrigation water withdrawals are especially high in the Nile Delta, the Po Valley, in the Eastern Mediterranean and in some Spanish regions. In total, the agricultural sector in the Mediterranean was simulated to withdraw approx. 223 km^3 of water per year for irrigation (average 2000–2009). Only around 128 km^3 of this amount represent the quantity of water directly required by plants (NIR). Hence, around 95 km^3 of water infiltrates, evaporates and leaks on the way to the plants before being productively used for photosynthesis.

Figure 2a shows irrigation water requirements (coloured in blue) and green water consumption on irrigated areas (coloured in green) in the Mediterranean region, ordered from the highest to the lowest NIR. Green water is the precipitation water stored in the soil and directly available for plants. Adding both values yields the crop water needs. Sugar cane production, mostly cultivated in Morocco and Egypt, is the most water-intensive crop of the region (Fig. 2a). Also date palms, citrus and olives have irrigation water requirements above 7000 $\text{m}^3\,\text{ha}^{-1}$. Nonetheless, when regarding to absolute values of NIR (not shown), as oppose to values per hectare, temperate cereals, maize, olives and cotton, with NIR above 10 km^3 each, are the strongest water consumers (see crop-specific irrigated areas in Fig. S1). Nevertheless, caution is imperative when interpreting both indicators (absolute and per hectare), since they represent averages and sums that are not independent from the location of cultivation areas and thus, are influence by the patterns of potential evapotranspiration.

Our simulations indicate that the Mediterranean region could save 35 % of water by strongly improving the irrigation systems and the conveyance infrastructure: GIR for the DRIP scenario amounts to $\sim 143\,\text{km}^3$. A less dramatic improvement (IMP) yields 10 % water savings ($\sim 200\,\text{km}^3$). Especially Egypt, Turkey, Spain and Syria could save large amounts of water through a switch to more efficient irrigation systems and infrastructure (Fig. 2b). On the contrary, for example Libya and Tunisia have not only lower irrigation water requirements but also much reduced possibilities for saving water through optimization of irrigation systems and conveyance (Fig. 2b).

Fader et al. (2015) found a general good agreement with other estimates for NIR at national and subnational levels and for GIR at national level. Souissi et al. (2013) compiled data from various sources, showing estimates of irrigation water use of 181 $km^3 yr^{-1}$ in 2005 for the Mediterranean region. It is unclear if they refer to net or gross irrigation, but this value is within the range defined by our NIR and GIR values (128 and 223 km^3, respectively). Blinda (2012) estimated the water demand for irrigation use at 181.3 km^3 in 2005 (Mediterranean area excluding Portugal, Serbia and Jordan) and the water lost during conveyance and distribution at 100 km^3. It is not clear how they computed or collect the data. These numbers are close to ours (223 and 95 km^3, respectively).

The ratio of NIR to GIR in our study is 57 % and represents the current irrigation efficiency. This is in very good agreement with Fischer et al. (2007) who calculated an irrigation efficiency of 58 % (average of Western Europe, including Southern Europe and Turkey, and the Middle East and North Africa).

Only rather old data from FAO (1986) on crop-specific water needs were found to compare with our estimates (see error bars in Fig. 2a). FAO values are very generic, i.e. without differentiation for period of time, region, climate and soil. The comparison yields a fair agreement with our values for some crops but shows that spatial-inexplicit data may overestimate the water needs for sugar cane, fodder grass, sunflower, tropical cereals and potatoes in the Mediterranean region.

3.2 Climate change will increase irrigation water requirements in the future

Without improvements in irrigation technologies and irrigation water conveyance (STD), considering no effects of higher CO_2 concentrations (CONST) and looking at the 5 °C warming trajectory, GIR increases around 18 % up to ~ 264 km^3 in 2080–2090 (median over 19 CGMs, Fig. 3). Full CO_2-fertilization effect (DYN) and the lowest warming level (2 °C) yield a much lower increase of about 4 % (Fig. 3). The influence of outlier GCMs was explored by calculating the GIR average over GCMs, which shows slightly higher values than the median (data not shown), demonstrating that results are very robust.

GIR in 2080–2090 will strongly depend on the irrigation technology used by the farmers and on the efficiency of the nation's conveyance systems (pipelines or open-canals). Figure 3 shows that this factor may have a larger influence than the strength of warming and the effect of higher CO_2 concentrations in the atmosphere (within every warming level, note the large differences between the different irrigation scenarios). Also, regardless of the warming level and the effect of CO_2-fertilization, strongly improving irrigation technologies and irrigation water conveyance (DRIP) until the end of the century would have the potential of saving around 30 % of water (compare bars from DRIP and solid, black line in Fig. 3).

Interestingly, the results for a limited improvement in irrigation technologies and irrigation water conveyance (IMP) are heterogeneous. For a 2 °C global warming, total withdrawal for irrigation is lower than current values. For a 3 °C warming, negative effects of climate change may counteract the gains achieved through the technological improvements. For 4 and 5 °C warming, the negative effects of climate change may overcompensate the savings, depending on the actual effect of CO_2-fertilization (Fig. 3).

Note that the RED scenario is not always at the same proportion between CONST and DYN since the implementation of this scenario (see Sect. 2) and the non-linear trajectory of CO_2 concentrations as shown in Fig. S2 made possible to account for a high diversity in the combination of the CO_2-fertilization effect and warming levels. For example, for 2 °C warming, the CO_2-fertilization in DYN and RED are assumed to be equal, while they separate for higher warming levels (see Fig. S2 for more details).

Souissi et al. (2013) compiled data from various sources using the database of the Blue Plan. They showed estimates of irrigation water use for 2025 in the range of 157 to 212 km^3 (compared to 181 km^3 in 2005), depending on the scenario (sustainable development in relation to water resources policies and business as usual). The values are naturally lower than ours (Fig. 3), very possibly due to the shorter time frame, but

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

they point out that both increases in irrigation water requirements as also potential savings in irrigation water are possible depending on the scenario chosen. This is in good agreement with our results.

The results shown in Fig. 3 represent medians and do not show the spread of results from different GCMs. Figure 4 shows for which areas there is a high agreement in NIR results, even using different GCMs as inputs. Under low warming and DYN most of GCMs compute that the Mediterranean agricultural plants would need slightly less water than today. However, 60 to 80 % of the GCMs also agree on increases in NIR of 15 to 45 % for some French regions (Fig. 4, upper left panel). With increasing warming, and even accounting for some realization of the CO_2-fertilization effect (RED), NIR increases between 15 and 45 % expand to the rest of the Mediterranean region. The GCM agreement under 4 °C (RED) is generally lower than for 2, 3 and 5 °C warming but still robust for large areas in Spain and Algeria (Fig. 4). Under high warming and excluding the CO_2 fertilization effect yields very high GCM agreement on important NIR increases, especially strong (> 80 %) in central France (Fig. 4, lower right panel).

The Fig. 2c in Konzmann et al. (2013), calculated for 19 GCMs, the SRES scenario A2 (warming between 2 and 5.4 °C globally) and constant CO_2-concentrations by the 20180s show similar patterns to our Fig. 4 (lowest panel), confirming robust, generalized increases in the Mediterranean region, excepting for Egypt. Also Haddeland et al. (2013) found comparable results, with increases in potential irrigation water consumption with increasing global mean temperature for Spain, Portugal and France. The Tables 5 and 6 in the study of Fischer et al. (2007) presented net irrigation water requirements aggregated after regions for 2 GCMs (SRES A2 and B1) by the end of the century and accounting for the CO_2-fertilization effect. They agree with our results in two points, first in stronger increases in net irrigation requirements with unmitigated climate change, and second, in stronger effect for Western and Southern Europe than for the Middle East and North Africa region.

All the changes shown in Fig. 4 are the result of complex interactions between the region's management intensity, the chosen mix of crops, the climate forcing as well as changes in physiological plants' responses (e.g. in the transpiration), and agronomic changes, such as length and beginning of growing period and yields. Section 3.4 gives some insights into this.

3.3 Population change may aggravate the water situation

Since some decisions and adaptation measures are taken in supranational institutions, for example at the levels of the European Union or the Arab Maghreb Union, we show here results aggregated after regions (Northern, Eastern and Southern Mediterranean. Eastern Mediterranean includes from Turkey to Israel and Jordan). Figure 5 shows an overview of future water withdrawal per region, accounting for climate change, CO_2-fertilization, technology improvements in irrigation systems and population change. The Eastern Mediterranean is today the highest water extractor, followed by the Northern Mediterranean, and with a smaller difference, by the Southern Mediterranean (red lines Fig. 5).

Climate change alone (without population change, CO_2-fertilization and transformation of irrigation systems) may increase gross irrigation water requirements 28, 16 and 11 % in the Northern, Eastern and Southern Mediterranean respectively (Fig. 5a). Full realization of the CO_2-fertilization effect may decrease these numbers to 17, 7 and 3 % (Fig. 5b).

Population growth in combination with stagnation in irrigation technologies, strong climate change and impossibility for realizing the CO_2-fertilization effect may drive GIR up to 185 and 118 km^3 in the in the Eastern and Southern Mediterranean, respectively (Fig. 5a). This would mean almost a doubling of current GIR in both regions (∼ 95 % increase in both regions). In the Northern Mediterranean, accounting for population change eases slightly the situation since population is expected to decrease in this region. However GIR still increases around 25 % because climate change overcompensates population decreases.

Improving irrigation technology and the efficiency of irrigation systems has large water saving potentials, especially in the Eastern Mediterranean (Fig. 5). However, it can compensate population growth and climate change only when combined with some degree of CO_2-fertilization effect. Looking at the most optimistic CO_2-fertilization scenario (DYN) in the Eastern and Southern Mediterranean, only the DRIP scenario delivers lower GIR than today, when increases due to population and climate change are accounted for (IMP is always above the red lines in Fig. 5b).

Comparing the red lines coincides with the bars or lower whiskers in Fig. 5a shows situations where the effects of climate and population change might compensate the water savings achieved through improvement/optimization of irrigation and conveyance systems: climate change would compensate gains through IMP (DRIP) in the Northern (Eastern) Mediterranean at 3 °C global warming if CO_2-fertilization does not take place (Fig. 5a). Even with some degree of CO_2-fertilization the Eastern and Southern Mediterranean would need more water than today already at 2 °C global warming if irrigation technology follows the IMP scenario.

Adding up over the subregion yields the magnitude of the influence of population change on total GIR: without changes in irrigation systems and conveyance, the Mediterranean region might face increases in NIR between 22 and 74 % (2 °C global warming combined with DYN and 5 °C combined with CONST, respectively).

Summarizing: assuming that (a) population change will take place, (b) all Mediterranean regions can afford some degree of modernization of irrigation and conveyance systems (IMP), and (c) CO_2-fertilization will happen to some degree, but nutrients limitations and other co-dependencies with other production factors will limit its positive effects (RED): the Northern Mediterranean will need less water than today, and the Eastern and Southern Mediterranean will need around 35 % more water than today, with the highest values under 3 and 5 °C global warming, respectively.

There is a general lack of analyses from other studies that can be compared with this section, but our results are in line with some global studies that detected a strong influence of population growth in other water related issues, for example in water scarcity indicators (e.g. Vörösmarty et al., 2000; Schewe et al., 2013).

The results presented until now give an overview when considering all agricultural products together. However, different crops present contrasting patterns of change, as shown in the next section.

3.4 Agricultural trees strongest affected

Figure 6 presents a summary of crop-disaggregated results for NIR change under different warming levels in the DYN and CONST CO_2-fertilization scenario (see the RED scenario in Supplement Fig. S4). Most of the crops will need more water per area under climate change, even if full CO_2-fetilization effect is accounted for (Fig. 6a). Grapes are the strongest affected crop with increases up to 30 % in the 5 °C warming track (DYN). Also all other agricultural trees, especially olives, nut trees, cotton and orchards, show high increases, which is especially drastic since they are already today major water consumers (compare Fig. 2a). For 2 °C warming increases are mainly limited below ∼ 8 %, but already at 3 °C warming, cotton, orchards and grapes are pushed above ∼ 10 % increases. The second strongest affected group of crops are the C4 crops (maize and sugar cane). Since these crops already have a high water use efficiency, gains through CO_2-fertilization are very limited and, thus, NIR increases between 7 and 9 % in the 5 °C warming trajectory. Groundnuts and rice are less strongly affected, but the areas of these two are very small in the Mediterranean region. The increases are much stronger when considering that CO_2-fertilization effect may not be realized: already at 2 °C warming NIR increases range up to 13 % (compare Fig. 6b).

NIR of some C3 annual crops (mainly food and oil crops) could decrease with increasing warming along with full CO_2-fertilization effect. The NIR reduction tends to saturate with increasing warming (Fig. 6a). Observing these crops in Fig. 6b leads to the conclusion that the NIR decreases are due to the CO_2-fertilization effect, i.e. in case of impossibility of realizing this effect, most C3 crops would face NIR increases.

The patterns observed in Fig. 6 are the results of complex, interlinked effect chains. Climatic variables and CO_2-concentrations affect directly irrigation requirements, for example through modification of soil evaporation and interception via modification of the atmospheric demand (potential evaporation). Climate change also affects irrigation requirements via indirect impacts on growing period length, sowing dates and, most importantly, agricultural yields (Fader et al., 2010). Figure 7 sheds light on this topic leading to two main conclusions.

First, the reduction in NIR of most C3 crops under full CO_2-fertilization effect seems to be produced by a predominance of higher water productivity (lower transpiration) over shortening of growing period and lower yield. The opposite seem to be true for perennial crops and C4 annual crops, where the stimulation of photosynthesis (and higher biomass production), the lengthening of growing periods and the positive changes in potential evapotranspiration seems to overcompensate the reduction in transpiration due to shorter opening times of stomata (compare Figs. 7a and 6a). These crops have both yield and NIR increases, being the yield increase stronger.

Second, yield increases peak for many C3 food crops at 3 °C, while yield increases of perennial fruit trees peak under 4 °C or even 5 °C (Fig. 7a). But most importantly, yield increases and the location of the yield peak depend on the realization of the CO_2-fertilization effect (Fig. 7b). Yield of many for the Mediterranean important crops like olives, orchards and vegetables will decrease already at low warming if CO_2-fertilization effect does not take place. Yield decreases and increases can be minimized and maximized, respectively, by limiting warming to 2 °C in case other limiting factors threaten the realization of the CO_2-fertilization effect (Fig. 7b).

These results are in good agreement with some detailed studies on specific crops. For example, Voloudakis et al. (2015) projected yield increases for cotton in Greece with warming between 2 and 4 °C using the AQUACROP model and accounting for the CO_2-fertilization effect. Tanasijevic et al. (2014) projected for 2050 18.5 % increase in irrigation water requirements of olive trees in the Mediterranean region. Saadi et al. (2015) projected for 2050 a decrease in irrigation water requirements of wheat by 11 % in the Mediterranean region.

3.5 Water scarcity may constrain future irrigation

This section closes the results' section by relating the calculated water requirements with the national water availability scenarios. In the most restricted scenario, i.e. accounting for population growth, 5 °C global warming, no realization of CO_2-fertilization, no improvements in irrigation technology and assuming that every country reserves 30 % of internal surface water for aquatic ecosystems (scenarios GIV_SUS and POL_SUS, see Sect. 2.4), Algeria, Libya, Israel, Jordan, Lebanon, Syria, Serbia, Morocco, Tunisia and Spain would not have enough water for satisfying irrigation requirements in 2080–2090. This is 10 out of 22 Mediterranean countries. The rest of the Mediterranean countries, mostly situated in the Northern Mediterranean, seem to have enough renewable water resources for meeting irrigation requirements in all scenarios.

6 of the countries that cannot meet irrigation water requirements (Algeria, Libya, Israel, Jordan, Syria and Serbia) would not be able to meet them even in the most optimistic scenario of climate change and irrigation technologies (DRIP, 2 °C warming, DYN CO_2-fertilization scenario).

The other 4 could potentially meet their irrigation requirements under some scenario combinations. Tunisia and Lebanon could do that by strongest improving irrigation and conveyance systems (DRIP) and assuring the beneficial effects of CO_2-fertilization (DYN or RED) if global warming would be limited to < 5 °C in the case of Tunisia and to < 3 °C in the case of Lebanon.

Morocco and Spain could meet their requirements already with a medium improvement of irrigation and conveyance systems (IMP) regardless of the warming level or while assuring that global warming stays < 3 °C.

The comparison between the POL_SUS and GIV_SUS scenarios indicates that Tunisia and Spain have more possibilities of meeting irrigation requirements if they assure the given external inflow from other countries through international treaties.

The comparison of all these scenarios with the ones without reserving water for environmental flow requirements (POL_UNSUS and GIV_UNSUS, see Sect. 2.4) gives an indication of countries that can be at risk of having trade-offs between food production and protection of aquatic ecosystems. This is the case of Algeria, Syria, Serbia, Tunisia, Morocco, Lebanon and Spain. In some scenarios these countries meet irrigation requirements only when not accounting for environmental flow requirements.

Caution is imperative when interpreting these results since they represent an optimistic scenario by comparing irrigation water needs with current water availabilities, i.e. they do not take into account increases in industrial and domestic water use or direct impacts of climate change on the water resources. A global multi-model assessment of climate change impacts on water resources yielded for most of the Mediterranean region strong and robust reductions in surface runoff (Schewe et al., 2013), a second study that takes into account current dams, practices and land use patterns also showed that reduction in surface runoff is likely in this region (Haddeland et al., 2013) but the uncertainty on the magnitude remains high. It is worth highlighting that the change in river discharge is especially uncertain among global hydrological models for the Eastern and Southern Mediterranean (Schewe et al., 2013).

Despites this, the figures shown in this section are mainly in line with the multi-model effort of Elliot et al. (2014), and confirm that future irrigation requirements will face water availability constraints, especially in the Southern Mediterranean. Also the study by Fischer et al. (2007), in spite of methodological differences, indicates that the Middle East and North Africa may be affected by a high water scarcity index (agricultural water withdrawal to internal renewable water resources up to 96 %) in 2080, designating potential difficulties for meeting future irrigation water requirements. For Europe including Turkey they have a much lower value (up to 10 %), which is also in good agreement with our results.

4 Conclusions and discussion

This study systematically assesses how climate change and increases in atmospheric CO_2 concentrations may affect irrigation requirements in the Mediterranean region in a context of demographic and technological change. The comparisons with other estimates presented in the result section reveal a strong robustness of our results that allows drawing some conclusions:

1. At present the Mediterranean region could save 35 % of water by implementing more efficient irrigation and conveyance systems. Some countries like Syria, Egypt and Turkey have higher saving potentials than others (e.g. Tunisia, Libya and France).
2. Without the positive effects of higher CO_2-concentrations in the atmosphere, a large proportion of climate model give a robust signal of increasing net irrigation requirements in the Mediterranean region at 3 °C global warming and beyond. This is the result of a spatial-explicit, complex interplay of modifications in growing periods, potential evapotranspiration, precipitation patterns and physiological responses.
3. Currently some crops, especially sugar cane and agricultural trees, consume in average more irrigation water per hectare than annual crops. Different crops show different magnitude of changes in net irrigation requirements, being the increases most pronounced in agricultural trees. The CO_2-fertilization effect can lower or counterpart the increases in NIR of some C3 annual crops.
4. Gross irrigation water requirements might increase or decrease depending on the future efficiency of irrigation and conveyance systems, the effect of population growth on food (and water) demand and the climate change impacts, while the first two seem to have the strongest influence. The Mediterranean area as a whole might face an increase in gross irrigation requirements between 4 and 18 % from climate change alone if irrigation systems and conveyance are not improved (2 °C global warming combined with full CO_2-fertilization effect, and 5 °C global warming combined with no CO_2-fertilization effect, respectively). Population growth increases these numbers to 22 and 74 %, respectively.

5. Subregional patterns of GIR change are complex and vary depending on the combination of climate change, irrigation technologies and CO_2-fertilization. The Northern Mediterranean might need less water than today, and the Eastern and Southern Mediterranean will need around 35 % more water than today assuming that population growth will increase food demand, all subregions can afford some degree of modernization of irrigation and conveyance systems (IMP), and CO_2-fertilization will happen to some degree (RED).
6. In some scenarios water scarcity may constrain the supply of the irrigation water needed in future in Algeria, Libya, Israel, Jordan, Lebanon, Syria, Serbia, Morocco, Tunisia and Spain.

4.1 Similar forcing, heterogeneous implications

As explained in the introduction, the amount of water needed for agricultural production in the Mediterranean region is a topic of economic and social relevance with political implications. The results of this study show that political incentives for water saving technologies as well as development of efficient public water conveyance systems may help to reduce water extractions already today but also under future climate change. This is especially true for the Eastern Mediterranean (Figs. 2b, 3 and 5).

Taking into account that irrigation water availability may be increasingly limited in future by competing uses, land use change, and climate change, the Mediterranean region may be very interested in supporting the limitation of climate change to of 2 °C global warming in order to potentially reduce irrigation requirements and require lower investments in irrigation technology and infrastructure. Already at 3 °C global warming, the investment and incentives needed to compensate climate change might be much more important than under 2 °C (Fig. 3).

Climate models deliver a consistent picture in the Mediterranean region: France seems to have the highest risk of suffering from higher irrigation requirements, even at low warming levels, but especially pronounced at high warming levels. The agreement of climate models for Spain, Turkey and Greece are shown to be especially strong in the case that the CO_2-fertilization effect cannot be realized (Fig. 4). For these countries, sustainable management of soil nutrients and soil water conservation techniques may help to benefit from the CO_2-fertilization effect.

The importance of drivers of change in irrigation requirements differs from region to region. Climate change may be the most threatening factor for the Northern Mediterranean, while population change combined with strong water scarcity seem to be the most important detrimental factors in the Eastern and Southern Mediterranean. Strong technological improvement may compensate the increases in irrigation requirements due to climate change in the Northern Mediterranean. In the Eastern and Southern Mediterranean a medium improvement of technologies even combined with low warming and full CO_2-fertilization effect would not be enough to avoid increases in gross irrigation water requirements (Fig. 5). And most importantly, these increased irrigation requirements have a high risk of not being met due to water scarcity (Sect. 3.5). In this context, governments of the Southern and Eastern Mediterranean may be interested in supporting climate change mitigation along with economic development in order to produce the financial means for virtual water imports, increasing sustainable water supply infrastructure and decreasing water demand of all sectors.

Improving irrigation technology is not the only way of coping with water scarcity. For example soil water conservation techniques, such as mulching and zero-tillage, may help to reduce irrigation requirements, especially in the regions where irrigation is meant to be a complement of rainfall. The influence of these factors is being analysed by a group at the Mediterranean Institute of Marine and Terrestrial Biodiversity and Ecology in order to explore adaptation options under climate change. Switching the type of crops within the agricultural areas may offer another adaptation option to cope with increases in irrigation requirements. Annual crops seem to be less prone to increases in irrigation requirements and decreases in yields than agricultural trees, being the relationships between both complex (Figs. 6 and 7). Given that agricultural trees are an essential part of the Mediterranean culture and agriculture, two implications can be drawn: first, governments may be interested in developing plans for protecting and supporting farmers linked to agricultural trees and perennial shrubs. And second, research agencies and researchers may be interested in focusing efforts for better understanding this kind of trade-offs and assessing the potentials for adaptation in more detail.

Another option for several countries is avoiding a direct relationship between food demand and population growth by increasing virtual water imports and improving agricultural management (additionally to improvements in irrigation technology) (see e.g. Fader et al., 2013). These are highly discussed topics with political, environmental and economic implications that would need careful planning for eluding self-induced food security risks. Other countries with high risk of depleting the water needed by aquatic ecosystems, like it is the case of Algeria, Serbia, Tunisia, Morocco, Lebanon and Spain (Sect. 3.5), may want to combine different strategies, first supporting climate change mitigation, second, changing their land use strategies, including changing crops, and third, developing monitoring systems that allow keeping control of water extractions in detriment of aquatic ecosystems.

Finally, collaboration, know-how transfer and cooperation in mitigation and adaptation, including a coordinated Mediterranean negotiation in the COP meetings may help the region to tackle the described challenges. As described in the next section, this has to go in hand with future research efforts aiming at both reducing the uncertainty of results and improving the understanding on the functioning of the Earth system as a managed space.

4.2 Strengths, weaknesses and perspectives for future research

This section offers an overview on the strengths and weaknesses of the present study and ideas for improving research on this topic in future.

One of the strengths of this study is the dynamic simulation of growing periods, sowing dates, crop varieties, and phenology in agricultural trees. This allows for more realistic estimates of future irrigation requirements since some adaptation options and changes in length of growing periods are already included in future simulations. However, the possibility of adapting through deficit irrigation (fulfilling only a part of vegetation water needs and thus lowering future irrigation water needs) was not accounted for. Challenges on the implementation of deficit irrigation are not only the complexity and non-linearity of the physiological response to low levels of water deficit, but also that these responses vary largely depending on the growth stage on which the water deficit is induced (FAO, 2002). Jägermeyr et al. (2015) recently made advances related to this topic and found in a sensitivity analysis that C4 plants can tolerate more water deficit in the soil than C3 plants.

The present study is focused on the water needs for keeping production and cultivation mainly on current irrigated areas. Land use change and irrigation expansion were considered in a simplified way through a linear relationship between food demand and demographic change. Future diet changes with associated land use shifts towards more meat and water-intensive products were not taken into account. There is a general lack of information on these issues, specifically on crop-specific land use patterns in future and this is the reason why this could not be taken into account. However, a recent global estimate yields a potential for compensating between 12 and 57 % of productivity loss caused by climate change around 2090 (RCP8.5) by expansion of irrigation (Elliot et al., 2014). Nevertheless, further research that includes various land use scenarios according to different drivers, accounting for groundwater dynamics, specifically including regional crops, and coupling water resources and vegetation growth is urgently needed for the Mediterranean area and will be part of future research efforts.

In the modelling framework used for simulating irrigation requirements plant growth is influenced by parameters representing different components of current agricultural management intensity (see also Fader et al., 2010). Assuming that nutrient deficits, soil erosion and salinization may limit the realization of the CO_2-fertilization effect, this study deals with the linked uncertainties by analysing different scenarios of CO_2-fertilization effect, and, for the first time, including an scenario of reduced CO_2-fertilization effect. This is one of the strengths of this study but points to the necessity of further model development towards a process-based representation of the phosphor, potassium and nitrogen cycles coupled with the photosynthesis and respiration routines (see e.g. Soussana et al., 2010). A research group in the Potsdam Institute for Climate Impact Research is working on tackling the implementation of the nitrogen cycle which will also open the possibility of better representing alternative farming practices. Also, one have to keep in mind that crops grown under increased CO_2-concentrations may have lower nutritional value and the realization of the CO_2-fertilization effect might require large efforts for managing efficiently all production inputs, which may represent an important challenge (Porter et al., 2014; DaMatta et al., 2010).

Our research shows large adaptive potential through implementation of drip irrigation and efficient conveyance systems (pressurized pipelines). High-tech irrigation systems may offer advantages such as conservation of fertilizers, reduction of water logging and higher yields due to high uniformity. However, less efficient irrigation and conveyance systems with high percolation and infiltration rates may have benefits, for example groundwater recharge, salt leaching, crop cooling, frost protection and high return flows in downstream areas, supporting food production and food security (e.g. Bastiaanssen et al., 2007). Thus, in order to avoid conflicts between up- and downstream water users, the effort must be put into local solutions based on integral management of water resources at the watershed level. Additionally to this point, drip and high-tech irrigation systems require high investment costs and high maintenance from qualified human resources for avoiding problems related to clogging and salinization (Belhouchette et al., 2012). Also farmers may use the saved water for planting higher values crops or base their crop choices rather on water productivity than on total water consumption. More research on the socio-economic and cultural constrains of the implementation of irrigation efficient systems and on complementary measures like climate smart agriculture, planting drought-resistant crops, rainwater harvesting and diversification of production systems is needed to bring these conclusions to the fields (Pedrick, 2012; Blinda, 2012).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |
Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀▮ ▮▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

When analysing the water saving potentials of more efficient irrigation systems and water conveyance infrastructure, we disregard the fact that more efficient irrigation systems usually require more energy (and higher investment costs). If this additional energy was to be provided by burning fossil fuels, a positive feedback would be created: climate change increase irrigation requirements that lead to technological transformation, that in turn leads to higher energy demand and finally to more fossil fuel burning and more climate change. Even if this disregard was intentional in order to assess non-energy limited potentials for adaptation, the non-fossil possibilities for supplying the energy needed for more efficient irrigation systems should be at the core of future research efforts.

The analysis on water scarcity carried out in the present study is a way of pointing out which countries could potentially face water shortage for future irrigation. Table S1 summarizes the characteristics, advantages and disadvantages of this approach. On the one hand these results are based on a rather optimistic scenario by comparing potential (not limited) irrigation water needs with current, renewable water availabilities at national level, i.e. they may mask subnational, seasonal patterns of water stress and they do not take into account future changes in industrial and domestic water use as well as direct impacts of climate change on the water resources. On the other hand, they may represent a pessimistic scenario by not considering fossil groundwater availability, desalination potentials and potentials for water recycling and reuse. The first point is justified by the continuously dropping groundwater levels (e.g. Wada et al., 2010) that might lead to water depletion in the near future. Regarding desalinization, water recycling and reuse, at the moment these processes are very energy and cost intensive (Elimelech and Phillip, 2011; Blinda, 2012), being their future development very uncertain. As important all these factors are, there are unknown variables and a general lack of data that constrain large improvements in the approach applied in the present study. Interdisciplinary efforts aiming at the development of socio-economic, technological and political scenarios that can be integrated with studies on impact of climate change on water resources are urgently needed to fill these gaps.

The model used for this study (LPJmL) includes a dynamic coupling of photosynthesis, water stress and CO_2-uptake (Gerten et al., 2004) and was recently further developed and successfully tested for including the most important crops in the Mediterranean region (Fader et al., 2015). Thus, LPJmL is probably the most complete, mechanistic agro-ecosystem model for the Mediterranean region at present. However, this study is focussed on potential net and gross irrigation requirements, i.e. we assumed that irrigation needs are always met and as a posterior step, we compare this needs with water availabilities. This implicitly constrains the assessment of production increases in water scarce regions through the supply of water saved in other regions as well as the assessment of “more crop per drop” potentials. The study of Jägermeyr et al. (2015) look into these issues for the present time and argue that transpiration and non-beneficial water consumption are not as closely related as previously assumed, i.e. it states that there are large potentials for producing more food with less water. Further research on the dynamics of this relationship under climate change is highly needed to complement our findings.

Summarizing, the present study offers new, detailed evidence about potential increases in water needs and possible water shortages for irrigation due to future climate and demographic change. These results are complemented by a comprehensive analysis on how Mediterranean societies could adapt to this situation by improving irrigation and conveyance systems.

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Table 1. Left part: efficiencies linked to irrigation and conveyance systems. EA = Field application efficiency. EC = Conveyance efficiency. Right part: explanation of the implementation of the improved irrigation scenario (IMP). For example, a country with surface irrigation and open channels, will improve in the IMP scenario to a combination of surface and sprinkler irrigation and to mixed conveyance system (channels and pipelines).

Current predominant irrigation system	Current conveyance system	EA	EC		Improved irrigation system	Improved conveyance system
Surface	Open channels	0.6	0.7	⟶	Mixed (surface/Sprinkler)	Open channels and pipelines
Mixed (surface/Sprinkler)	Open channels and pipelines	0.675	0.825	⟶	Sprinkler	Pipelines
Sprinkler	Pipelines	0.75	0.95	⟶	Drip	Pipelines
Drip	Pipelines	0.9	0.95	⟶	Drip	Pipelines

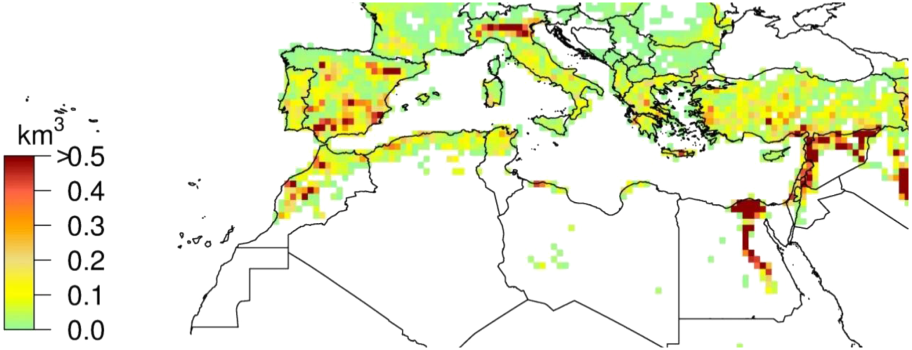

Figure 1. Annual absolute gross irrigation water requirements GIR, as average for the period 2000–2009, at 30 arc minutes resolution.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

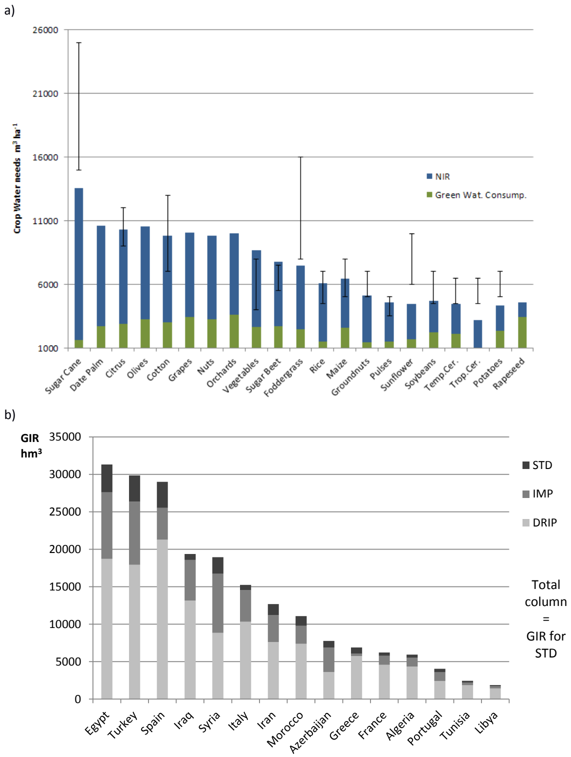

Figure 2. (a) Net irrigation requirements and green water consumption aggregated for different crops in the Mediterranean region, as average of 2000–2009. Total bar height represents the crop water needs. Error bars show the maximum and minimum values for crop water needs published by FAO (1989). Note that the y axis cut at $1000\,\mathrm{m}^3\,\mathrm{ha}^{-1}$. **(b)** National gross irrigation water requirements (GIR) for current irrigation systems (STD), improved irrigation systems (IMP) and optimized irrigation systems (DRIP) as average for the period 2000–2009.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

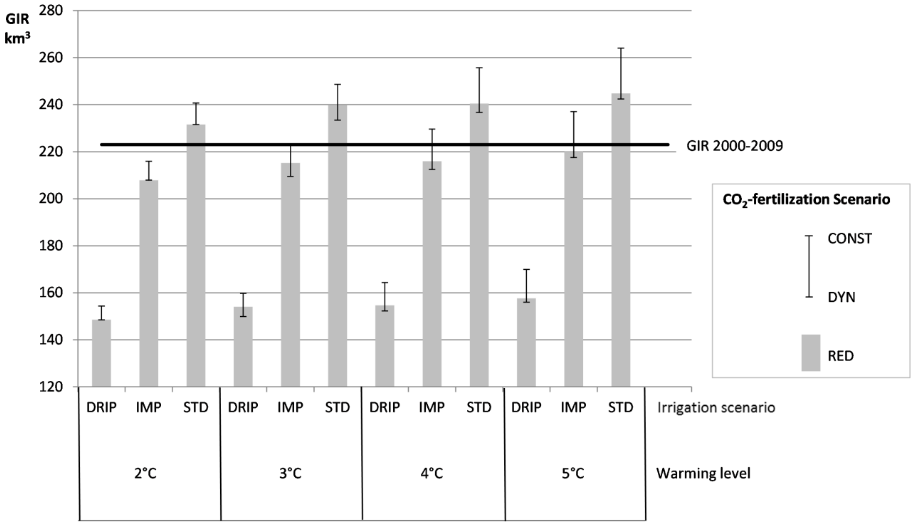

Figure 3. Median (19 GCMs) of gross irrigation water requirements GIR for 5 warming levels, 3 irrigation scenarios (STD, IMP, DRIP) and 3 CO_2-scenarios (column represents RED and whiskers, DYN and CONST). Period 2080–2090, for the Mediterranean region as a whole. Note that the x axis cuts at 120 km^3.

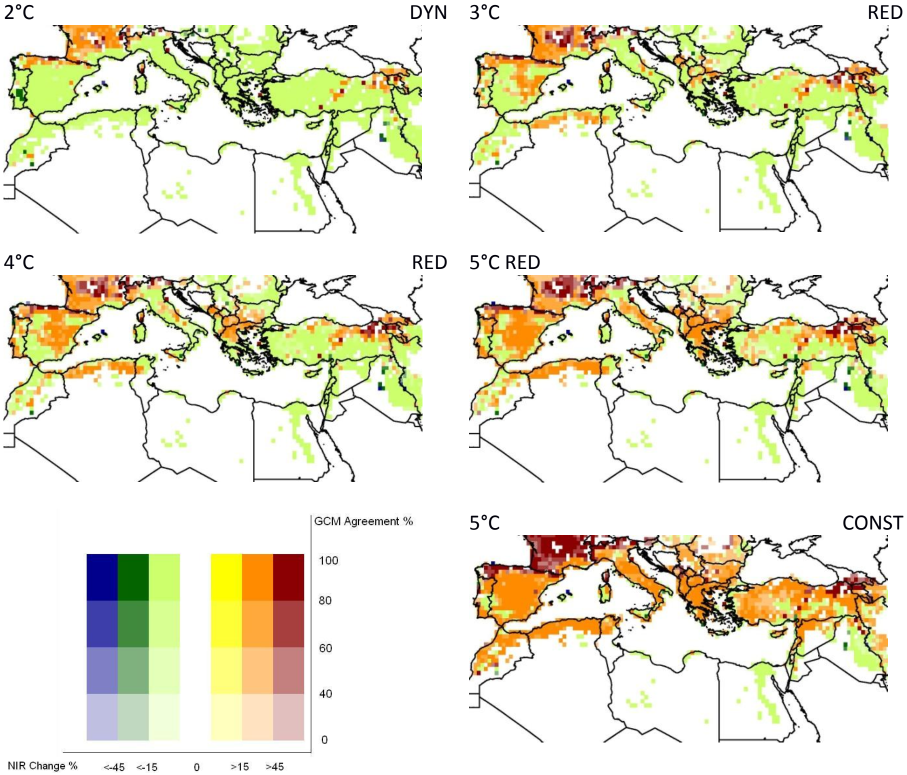

Figure 4. Change in per unit of area net irrigation water requirements NIR from 2000–2009 to 2080–2090, and GCM agreement (saturation), for 2 to 5 °C warming combined with different CO_2-scenarios. See Supplement (Fig. S3) for all scenarios ordered after warming level.

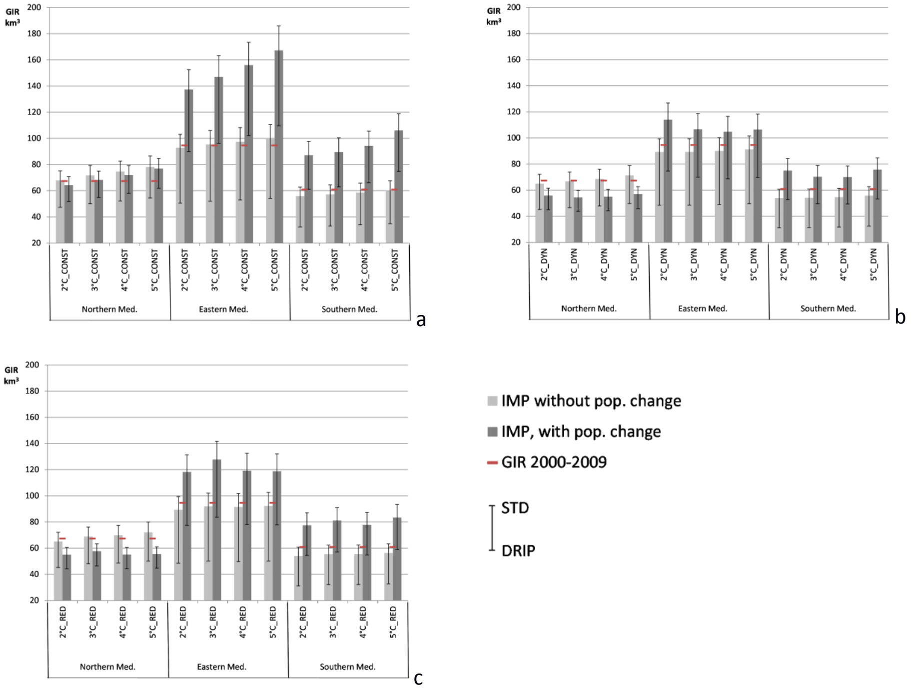

Figure 5. Regional gross irrigation water requirements GIR as median over 19 GCMs for the period 2080–2090 for different combinations of warming and CO_2-fertilization effect (x axis), different irrigation scenarios (bars represent the IMP scenarios, whiskers the STD and DRIP scenario), and with and without consideration of demographic change (light grey bars: without population change; dark grey bars: with population change). Current regional GIR is represented by the red lines. Note that the x axis cuts at 20 km^3.

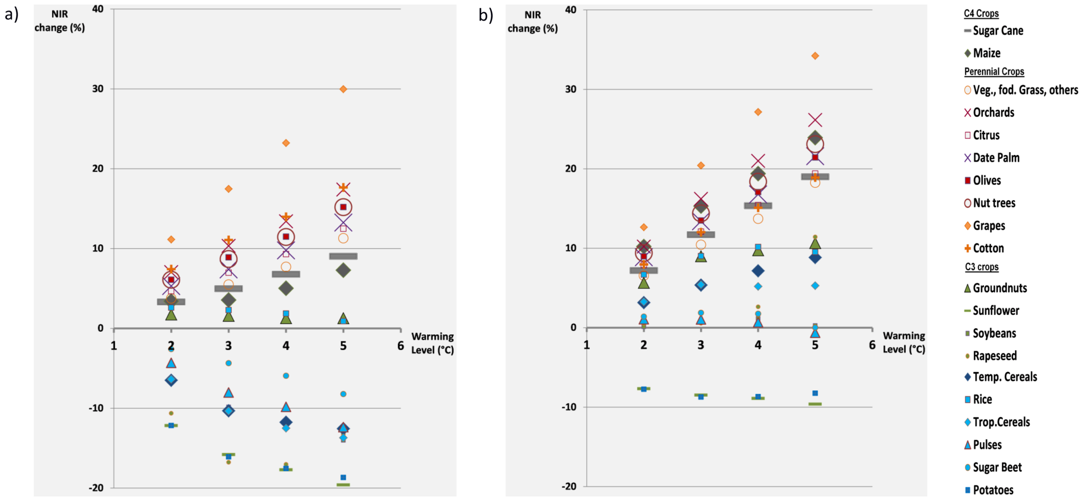

Figure 6. Change in per unit of area net irrigation water requirements NIR from 2000–2009 to 2080–2090 for different crops' classes and the DYN **(a)** and CONST **(b)** CO_2-fertilization scenario. Negative (positive) values indicate a decrease (increase) in NIR (see Fig. S4 in Supplement for the RED scenario).

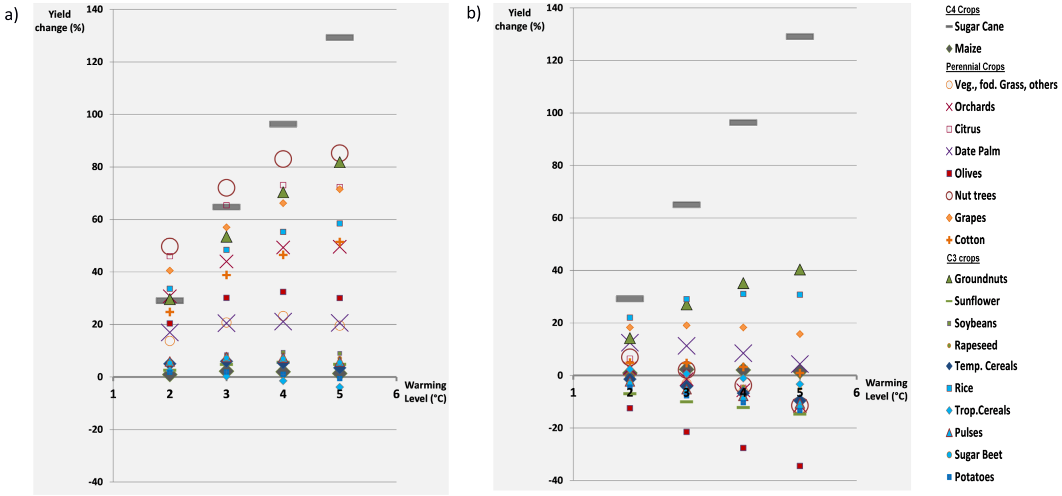

Figure 7. Change in yields from 2000–2009 to 2080–2090 for different crops' classes and the DYN **(a)** and CONST **(b)** CO_2-fertilization scenario. Negative (positive) values indicate a decrease (increase) in yields (see Fig. S4 in Supplement for the RED scenario).