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Water and energy footprint of irrigated agriculture in the Mediterranean region

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Abstract

Irrigated agriculture constitutes the largest consumer of freshwater in the Mediterranean region and provides a major source of income and employment for rural livelihoods. However, increasing droughts and water scarcity have highlighted concerns regarding the environmental sustainability of agriculture in the region. An integrated assessment combining a gridded water balance model with a geodatabase and GIS has been developed and used to assess the water demand and energy footprint of irrigated production in the region. Modelled outputs were linked with crop yield and water resources data to estimate water ($m^3\ kg^{-1}$) and energy ($CO_2\ kg^{-1}$) productivity and identify vulnerable areas or 'hotspots'. For a selected key crops in the region, irrigation accounts for 61 $km^3\ yr^{-1}$ of water abstraction and 1.78 Gt CO_2 emissions yr^{-1}, with most emissions from sunflower (73 kg CO_2/t) and cotton (60 kg CO_2/t) production. Wheat is a major strategic crop in the region and was estimated to have a water productivity of 1000 t Mm^{-3} and emissions of 31 kg CO_2/t. Irrigation modernization would save around 8 km^3 of water but would correspondingly increase CO_2 emissions by around +135%. Shifting from rain-fed to irrigated production would increase irrigation demand to 166 $km^3\ yr^{-1}$ (+137%) whilst CO_2 emissions would rise by +270%. The study has major policy implications for understanding the water–energy–food nexus in the region and the trade-offs between strategies to save water, reduce CO_2 emissions and/or intensify food production.

Keywords: food security, CO_2 emissions, nexus, water productivity, water resources

1. Introduction

Agriculture plays a vital economic role in the Mediterranean region. It employs more than a fifth of the population in 50% of the countries and contributes >10% GDP in eight countries alone (Mediterra 2009). The Mediterranean region in this study refers to the 21 countries surrounding the Mediterranean Sea in addition to Portugal and Jordan. Mild winter temperatures and long hot dry summer's that are characteristic of this region make it ideal for growing a diverse range of crops including olives, citrus, vineyards and cereals, as well as high-value horticulture. As precipitation across the region is subject to high inter-annual and seasonal variability (Correia *et al* 2009), irrigation is an essential component of production for many farmers as it supports crop diversification, helps assure yield and quality and helps to stabilize food supplies (Hanjra and Qureshi 2010).

The irrigated area in the Mediterranean region has doubled over the last forty years and now represents a fifth (21%) of the total cultivated agricultural land in the region (Plan Bleu 2008). Between 1981 and 2001, the largest increase in irrigated area was in Syria (+124%), Algeria (+114%), Jordan and Libya (+109%), which explains why 81% total water demand in Eastern and Southern Mediterranean countries is used to support irrigated agriculture (Aquastat 2013). Surface (gravity fed) irrigation is still the most widely used technique despite its relatively poor application efficiency. Nevertheless,

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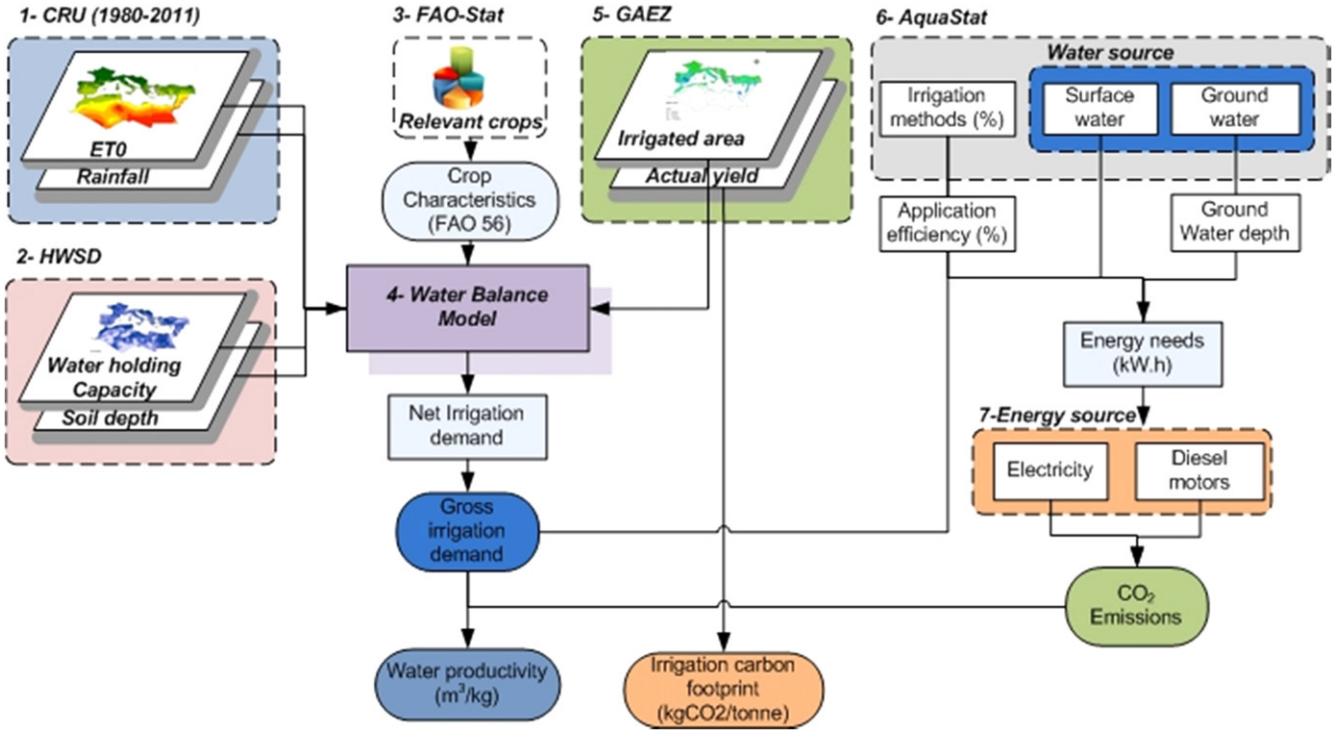

Figure 1. Schematic summarizing the methodology developed to assess the water and energy needs of Mediterranean irrigated agriculture.

large expansion of irrigated lands using overhead pressurized sprinkler systems has been reported in North Africa (Ragab and Prudhomme 2002).Water is needed not only to support agriculture but also to meet the domestic needs of a growing population, to enhance living standards and support industrial manufacturing processes and tourism (World Water Assessment Programme 2009).

The availability and reliability of water resources is a limiting factor for economic development in many water-stressed countries. The Mediterranean region is one of the most water scarce regions globally. Water is particularly scarce in Southern and Eastern countries and in some catchments in the North, such as South East Spain and the Ebro Depression, where the expansion of irrigated production, coupled with tourism and urbanization has created significant water supply challenges (García-Ruiz *et al* 2011). For example, in Libya, Egypt, Syria, Malta and Jordan, annual water withdrawals are higher than the volumes of renewable resources available within their territories. The shortfall is met from external resources (transfers through the Nile), abstraction of fossil water (non-renewable) and from non-conventional resources (treated waste water, desalination). A changing climate with rising temperatures and shifts in the spatial and temporal distribution of rainfall is likely to impact on crop productivity and food security (Knox *et al* 2012). Irrigation is regarded as one of the main adaptations to support crop production in response to climate change and population growth (Hanjra and Qureshi 2010). However, any increase in irrigation demand will correspondingly impact on energy consumption and greenhouse gas emissions suggesting potential conflicts in terms of mitigation and adaptation policies (Mushtaq *et al* 2013, Carrillo Cobo *et al* 2014a).

2. Methodology

This study describes a combination methodology to assess agricultural water demand in the Mediterranean region and estimate the CO_2 emissions associated with abstraction (pumping). It highlights the interactions between water use, food production and energy consumption and focuses on the environmental impacts associated with changes in irrigation technology and abstraction management. The trade-offs between reducing water consumption and CO_2 emissions are evaluated. Data on current levels of yield were then used to quantify water productivity and CO_2 emissions per unit of produce. The outputs were then compared against current water resources availability to identify food production 'hotspots'.

At the core of this study is a 0.5° gridded monthly water balance model that uses spatial and statistical datasets to estimate the water productivity and carbon footprint of irrigated agriculture in the Mediterranean region. Water demand was computed from 30 years historical climate data for typical irrigated crops grown in the region based on statistics (FAOSTAT 2013). The energy (kW h) to abstract and apply the water demanded were then calculated and transformed into CO_2 emissions using national data on water sources, irrigation methods and sources of energy. Finally, water demand and CO_2 emissions were compared against actual crop yields to estimate the spatial distribution of water productivity (kg m^{-3}) and the irrigated carbon footprint (kg CO_2/t across the basin. A description of the method and datasets used are described below and summarized in figure 1.

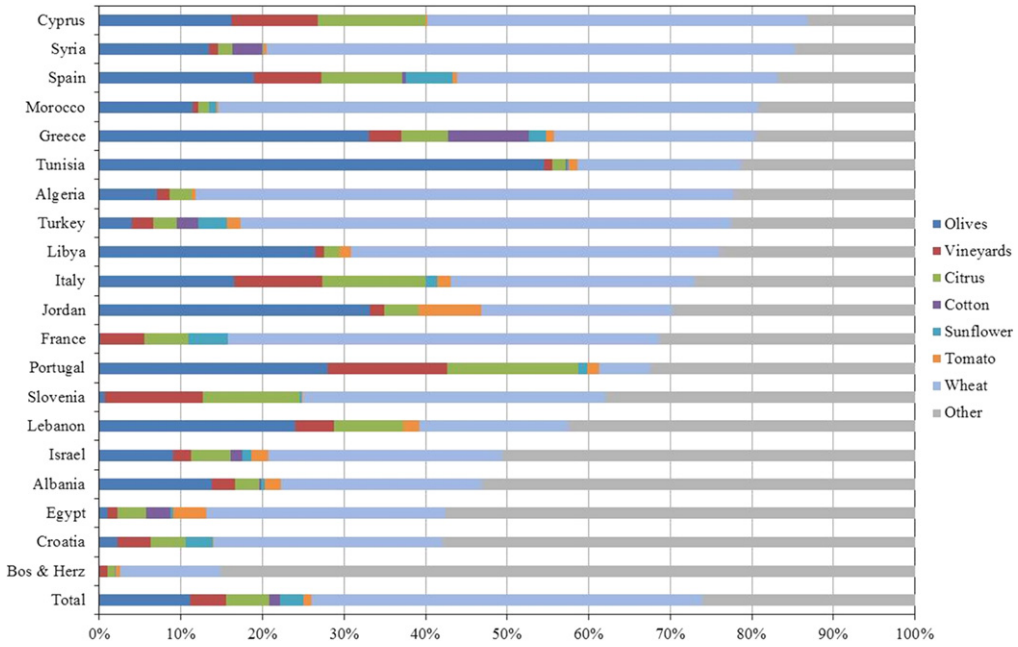

Figure 2. Proportional (%) split in cropping in the Mediterranean region (derived from FAOSTAT 2013).

2.1. Digital datasets

Climate data was based on the high resolution (0.5° × 0.5° latitude/longitude) gridded climate dataset (CRU TS3.20) developed by New *et al* (2000) updated by Mitchell and Jones (2005) and Harris *et al* (2013). This provides a global monthly climate gridded dataset extending for 1901–2011. Primary variables (precipitation, mean temperature and diurnal temperature range) were interpolated directly from station observations while secondary variables (wet day frequency, vapour pressure, cloud cover and ground frost frequency) were interpolated from merged datasets of station observations and from synthetic data estimated using predictive relationships with primary variables. Maximum and minimum temperature were arithmetically derived from previous parameters while potential evapotranspiration (PET) was calculated using a variant of the Penman–Monteith method (Harris *et al* 2013). In this study, monthly gridded PET and precipitation data for the Mediterranean basin for 1980–2011 was used to estimate the crop water requirements.

Soil parameters required to run the water balance model (available water holding capacity and soil depth) were extracted from the Harmonized World Soil Database (HWSD). This is a 30 arc second raster database containing over 16 000 different soil mapping units combining existing regional and national soil information (SOTER, ESD, Soil Map of China, WISE) with data contained within the 1:5 000 000 scale FAO-UNESCO Soil Map of the World (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). Gridded data on land use, irrigated areas and crop yield at 5 arc minute resolution were obtained from Module VI of the Global Agro-Ecological Zones (GAEZ) (FAO/IIASA 2010). In this module, cropped areas and reported yields were obtained by downscaling agricultural statistics for the main food and fibre crops from national data for 2000 and 2005. Agricultural statistics were derived mainly from the Food and Agriculture Organization of the United Nations (FAO) statistical (AQUASTAT 2013 and FAOSTAT 2013). The GAEZ Module VI first estimates the proportional split between rain-fed and irrigated cultivated land and then estimates the area, production and yield for each crop type (FAO/IIASA 2010). An iterative downscaling procedure was used to ensure that the cropped areas and production statistics were consistent with the aggregated statistical data and with spatial land cover patterns obtained from remotely sensed data.

Fan *et al* (2013) derived a global dataset containing observations of water table depth from government archives and associated literature. Data gaps were filled using a groundwater model forced by modern climate, terrain and sea level to infer the pattern of the groundwater depth at a 30 arc second grid resolution. In this study, knowing the depth to groundwater was essential to estimate lift (m) and CO_2 emissions due to pumping. A GIS was then used to extract and combine the relevant information from the climate, soil and land use databases to run the water balance model at a 5 arc minute grid resolution.

The Mediterranean climate makes it well suited to growing a variety of crops under both rain-fed and irrigated production. Therefore, to estimate irrigation water demand in the region it was necessary to first simplify the complex cropping pattern that exists and use representative crops for certain crop categories. Drawing on national statistics (FAOSTAT 2013), wheat represents nearly half (48%) the total cropped area in the Mediterranean region, followed by olive trees (11%), citrus (5%), vineyards (4%) and sunflower (3%). These proportions of course differ between individual countries depending on physical (local soil and agroclimatic) and agro-economic conditions. For example, olive trees account for over half (55%) the total cropped area in Tunisia;

Table 1. Water sources used for irrigation (%), relative split between application methods (%) and estimated CO_2 emissions per unit of kW h electricity ($gCO_2\ kW^{-1}\ h^{-1}$) by country (source: Aquastat 2013, IEA 2012).

	Water source (%)		*Application method (%)*			
Country	Ground water	Surface water	Surface	Sprinkler	Drip	$gCO_2\ kW^{-1}\ h^{-1}$ (source: IEA)
Albania	14	86	90	10	0	2
Algeria	70	31	82	9	9	548
Bos & Herz.	24	76	0	37	62	729
Croatia	10	90	51	46	3	305
Cyprus	52	48	15	5	80	702
Egypt	2	98	89	5	6	450
France	36	64	4	92	4	79
Greece	13	87	36	53	11	718
Israel	69	31	8	17	75	689
Italy	29	71	61	25	14	406
Jordan	59	41	18	1	81	566
Lebanon	52	48	64	28	8	709
Libya	99	1	5	89	6	885
Macedonia	94	6	0	37	62	687
Morocco	30	70	83	10	7	718
Portugal	0	100	79	11	10	255
Serbia & Mont.	94	6	0	37	62	724
Slovenia	30	70	0	37	62	325
Spain	21	79	30	23	48	238
Syria	28	72	78	14	8	594
Tunisia	64	36	59	25	17	463
Turkey	21	79	88	9	3	460
West Bank	59	41	27	21	52	689

vineyards account for 15% of agricultural land in Portugal. Two thirds (66%) of agricultural land in Syria, Morocco and Algeria is used for wheat production (figure 2). Olive trees, citrus, vineyards and wheat are the most strategic, traditional and representative crops of the Mediterranean region. Sunflower and cotton were also chosen to represent typical energy and industrial crops, respectively. The Mediterranean climate is also conducive to vegetable production; tomato was therefore selected to represent a typical vegetable cash crop. Collectively, these crops constitute three quarters (74%) of all Mediterranean agriculture. A final category, termed 'other', was defined to represent minor crop types in the region (figure 2).

National data on water resources (surface and groundwater), withdrawals (abstraction) and irrigation methods were obtained from the FAO global water information system (Aquastat 2013) (table 1). Water abstracted from groundwater was assumed to require additional pumping energy (lift) compared to direct abstraction from surface (river/lake) sources. For simplicity, energy for conveyance from source to field was ignored and hence the water source was assumed to be on-farm. Three application methods are used in agriculture, (i) drip, also known as trickle or micro irrigation, involves applying small frequent amounts of water slowly into the root zone, through a network of pressurized valves, pipes and emitters, (ii) sprinkler irrigation is a pressurized method where water is distributed and applied overhead using fixed or moving sprinklers, and (iii) surface irrigation, is where water is distributed by gravity-fed open channels and applied directly to the soil via syphons or gated valves into furrows, basins or border strips (Hedley *et al* 2014). Since gravity is used, no other structures (pumps, filters) are required and thus surface irrigation is the cheapest water application method. It also dominates Mediterranean and global irrigated agriculture (table 1). Matching irrigation method to crop must take into account soil and field characteristics, local climate conditions and reliability of water supply. For example, surface irrigation may be inefficient under light sandy soils as large volumes can be lost by deep percolation, but is well suited to large-scale extensive cropping. Sprinkler irrigation has the greatest potential on light soils and undulating fields and is well suited to high-value horticultural crops. Drip irrigation has the highest capital cost and is used on high value cropping (citrus and vineyards) where the benefits exceed cost and where water is expensive and/or scarce (Daccache *et al* 2010).

2.2. Water demand modelling

The volumetric irrigation demand for each crop grown in the region was calculated using a one dimensional monthly time step soil water balance model, running at a grid resolution of 0.5°. Model inputs included the global climate dataset for 1981–2011 extracted from the CRU database (Harris *et al* 2013), soils information from the 1:5 000 000 HWSD dataset (FAO/IIASA/ISRIC/ISSCAS/JRC 2012) and FAO land use data (FAO/IIASA 2010). Monthly water needs (I) in

each grid cell were calculated using the following equation:

$$I_i = \mathrm{ET}_{ci} - P_i + \mathrm{RO}_i - \delta w_i - G_i. \quad (1)$$

Where P_i is the amount of precipitation in month i (mm); RO is the surface runoff (mm); $\mathrm{ET_c}$ is the crop evapotranspiration (mm), G is the water capillary rise, and δw is the soil moisture content in the root zone (mm). The fraction of effective rainfall (P_{eff}) available to each crop type was estimated using the empirical formulae derived from the USDA Soil Conservation Service (USDA 1967). This excludes the volume of water lost by run off/ intercepted by plants.

$$P_{\mathrm{eff}(i)} = \left(\frac{P_{(i)}}{125}\right) * \left(125 - 0.2\,P_{(i)}\right), \quad \text{for} \quad P_{(i)} \leqslant 250 \ \text{mm}, \quad (2)$$

$$P_{\mathrm{eff}\,(i)} = 125 + 0.1\,P_{(i)}, \quad \text{for} \quad P_{(i)} > 250 \ \text{mm}. \quad (3)$$

Due to the deep aquifers in the Mediterranean region (Fan *et al* 2013), the water table interaction with the unsaturated zone is insignificant and therefore water capillary rise (G) was ignored. Crop evapotranspiration ($\mathrm{ET_c}$) was defined as the water flux to the atmosphere through soil evaporation and plant transpiration and calculated using the well-established single crop coefficient approach (K_c) as described by Allen *et al* (1998)

$$\mathrm{ET_c} = K_c * \mathrm{ET_0}. \quad (4)$$

Where $\mathrm{ET_0}$ is reference evapotranspiration and represents an index of climate demand and K_c (crop coefficient) is a crop factor predominantly affected by crop characteristics and plant growth stages.

This approach assumed optimal nutrient and water conditions with no limitations in crop development or evapotranspiration due to soil water or salinity stress, pests, diseases, weeds or low fertility. The effects of both crop transpiration and soil evaporation are integrated into a single crop coefficient (K_c). The procedure for estimating $\mathrm{ET_c}$ consisted of identifying appropriate growth stages (and length) for each crop type, selecting the corresponding K_c coefficients from Allen *et al* (1998) and finally calculating $\mathrm{ET_c}$ as a product of $\mathrm{ET_0}$ and K_c. For irrigation planning (scheduling) purposes and for most hydrological water balance studies including large-scale national (country) level assessments (this study), the use of the single crop coefficient approach is considered relevant. However, where assessments are required for individual fields and/ or for specific years or where atypical management strategies are being adopted (e.g. deficit irrigation) then separate K_c values on a daily time-step to account for transpiration and evaporation should be used (Allen *et al* (1998)).

The annual net crop water needs (mm) within each grid cell for each crop type were calculated for 1981–2011, then averaged and combined with land use data (ha) to estimate the net irrigation water demand ($\mathrm{m^3}$) for the Mediterranean region in an average year. However, even under optimal management practices, not all irrigation water applied is used. Losses are caused by runoff, evaporation and non-uniformity of application. These are largely dependent on the method of irrigation. For example, surface irrigation typically has a low application uniformity and theoretical efficiency of around 60% (Brouwer *et al* 1989). Sprinkler systems are generally better, with efficiencies of around 80% unless distorted by wind, whilst drip irrigation can have efficiencies exceeding 90% but only if well-designed and maintained (Brouwer *et al* 1989). The efficiencies assumed in this study to estimate gross water demand were indicative recognizing that operation and maintenance play a key role in influencing actual efficiency. The application efficiency values were weighted based on the proportion of each method used in each country taking into account the suitability of the method to crop type (table 1). For example, wheat can only be irrigated with surface and overhead irrigation, whilst olives and vineyards are typically irrigated using either surface or drip irrigation.

2.3. Energy requirements and CO_2 emissions

CO_2 emissions from irrigation were calculated based on the energy needed for abstraction (pumping) and water application. The energy used for abstraction is a function of water source. In this study, the energy required to abstract water from a surface source was assumed to be negligible; only energy (lift) for groundwater abstraction was included. This assumes that water is conveyed to the farm by gravity and not pressurized, but it is recognized that the water source is not always in close proximity to a farm, nor at the same/higher piezometric level. Pumping lift (m) data were derived from the global water table depth dataset (Fan *et al* 2013) and weighted depending on the mix of abstraction sources in each country, as identified by the global water information system (Aquastat 2013) (table 1).

The energy required for operating an irrigation system needs to take into account the nominal operating pressure (H_{min}) of the application method (drip/sprinkler) and friction losses (f_{Losses}) associated within the piped distribution system. The nominal operating pressure of sprinklers or drippers differs depending on the type and design but for each system manufacturer published data were used to identify the range in optimal operating pressure. Typical operating pressures (H_{min}) for drip (1 bar) and a medium sized sprinkler (3 bar) were assumed. The difference in pressure between the drippers/sprinklers of the system should typically not exceed 20% as this affects uniformity of water application. Therefore, 20% of the nominal discharge (H_{min}) was used to offset friction losses associated with the piped systems; a typical assumption used when designing on-farm irrigation systems. The total pressure head (TH) required to pump and apply water can therefore be calculated as:

$$\mathrm{TH}_{(\mathrm{m})} = \mathrm{Lift}_{(\mathrm{m})} + H_{\mathrm{min}\,(\mathrm{m})} + f_{\mathrm{Losses}\,(\mathrm{m})}. \quad (5)$$

The energy required (kW h) to pump the irrigation volume ($\mathrm{m^3}$) at the desired total pressure head (TH) was calculated using the following equation:

$$\mathrm{Energy\ (kW\ \ h)} = \frac{\mathrm{Volume}\left(\mathrm{m^3}\right) x\ \mathrm{TH\ (m)}}{367 \mathrm{x}\ \mu_{\mathrm{pump}} \mathrm{x}\ \mu_{\mathrm{motor}}}. \quad (6)$$

Where μ_{pump} and μ_{motor} represents the pump and motor efficiency, respectively. A pump efficiency of 80% was

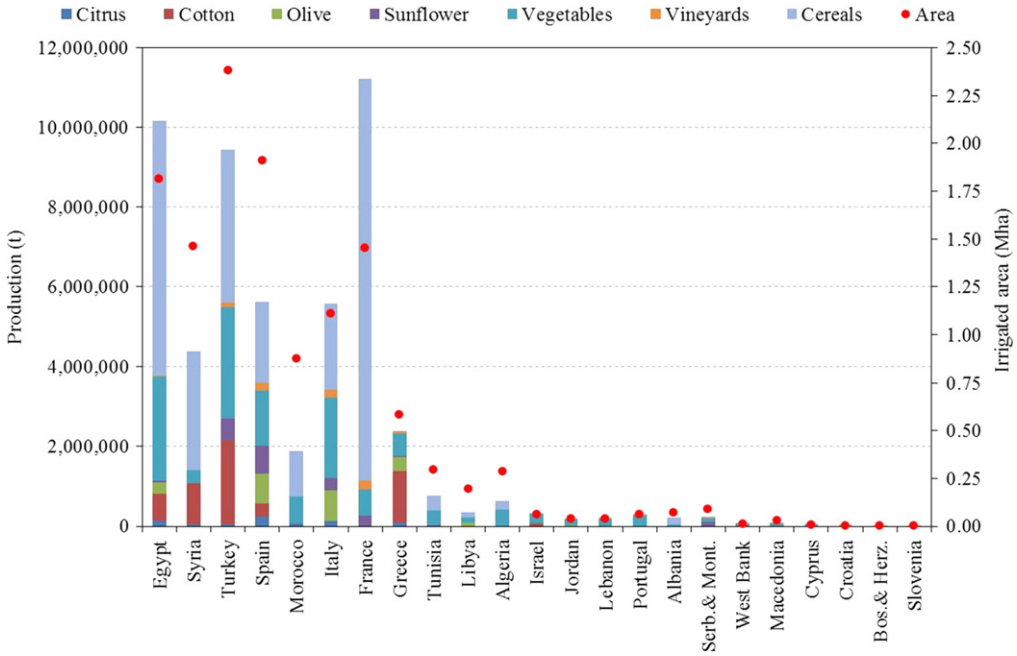

Figure 3. Total production (*t*) and irrigated area (Mha) by crop category for each country in the Mediterranean region.

assumed as this represents a typical value for a pump sized to match a designed system. Irrigation pumps are normally powered by diesel or electric engines. Diesel engines are not the most efficient in producing 'shaft power'. In fact, most of the energy produced is dissipated from the radiator or from the exhaust pipe leaving about 40% (μ_{motor}) as useful power for pumping. In contrast, an electric motor has a much higher efficiency with a typical ability to convert 90% (μ_{motor}) of energy produced into output power (Keller and Bliesner 1990). Due to a lack of data on energy sources used in pumping irrigation it was assumed that half the pumps in the Mediterranean were diesel powered ($\mu_{motor} = 40\%$) and the other half electric ($\mu_{motor} = 90\%$).

The energy source used also determines the quantity of CO_2 emitted for each kW h of energy produced. For example, the estimated CO_2e emitted from a diesel engine to produce 1 kW h of energy is equivalent to 0.2517 kg (Hill *et al* 2012). For electric motors, the energy to CO_2 conversion factor depends on the energy source from which the electricity is produced. For each country, the International Energy Agency (IEA 2012) has calculated the energy to CO_2 conversion factor using the total CO_2 emissions from fossil fuels consumed for electricity generation divided by the outputs of electricity generated from fossil fuels, nuclear, hydro, geothermal, solar, wind, ocean and biofuels (table 1). These conversion factors for both diesel and electric engines were used here to estimate the total volume of CO_2 emitted by irrigation pumping. Although renewable energy sources are being considered as an alternative source to reduce energy costs, and they could become the preferred option in future, currently their use in irrigation remains very limited (Carrillo Cobo *et al* 2014b).

3. Results and discussion

3.1. Irrigation water demand

France is the largest cereal producing country in the region, followed by Egypt and Turkey (figure 3). It accounts for around 30% of total production but has a very low total water demand (3%) due to high levels productivity as well as relatively low water demanding agroclimatic conditions. Average water productivity for cereals in France is estimated to be 6 kg m^{-3} compared to 1 kg m^{-3} in Turkey and Egypt. Three countries (Turkey (19%), Spain (15%) and Egypt (14%)) account for almost half the total irrigated area (figure 3), producing more than half the irrigated citrus (55%), cotton (57%), sun flower (62%) and vegetables (52%) with a total average annual water demand exceeding 32 km^3.

The average irrigation water demand for the major irrigated crops in the Mediterranean region were estimated to be around 61 km^3 based on a 40 year period (1970–2010). Most demand is concentrated in Egypt (14 km^3), Turkey (11 km^3), Syria (11 km^3) and Spain (8 km^3). Cereals account for over half the total irrigated area and near half (44%) the irrigation demand (figure 4). Vegetables and cotton are also important with 23% and 19% of the total water demand, respectively (figure 4). Despite their traditional and economic importance in the region, olive orchards and vineyards account for only 6% and 2% of demand, respectively, reflecting the fact that only 8% of olive trees and 23% of vineyards are currently irrigated.

3.2. CO_2 emissions

The water source, water table depth, irrigation method and volumetric water demand all combine to determine the energy needed for abstraction (pumping) and application. Our

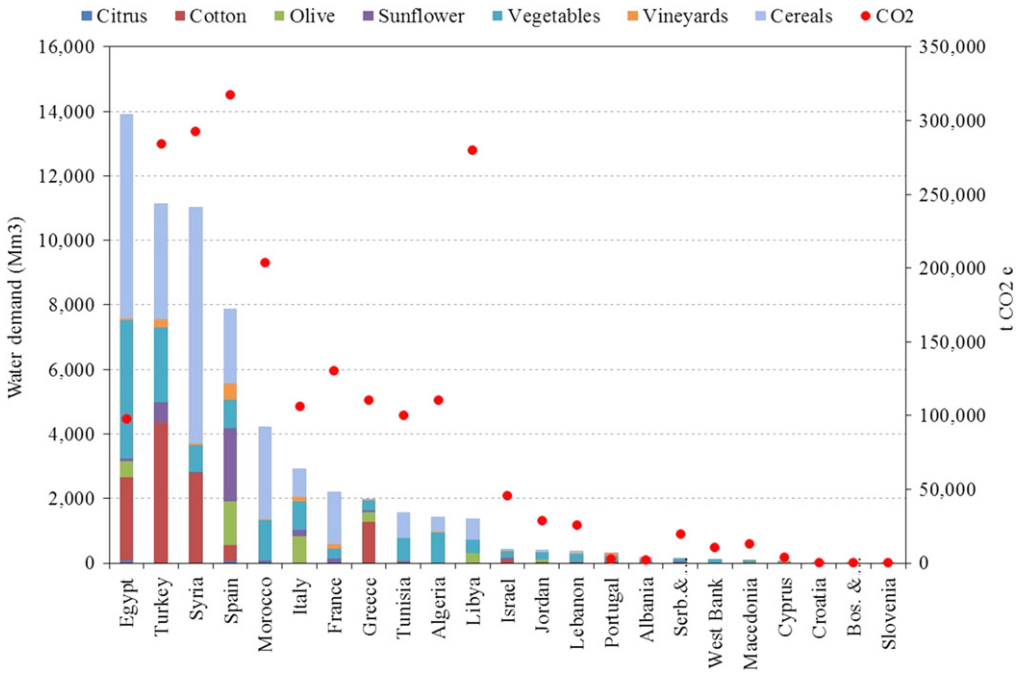

Figure 4. Estimated irrigation water demand (Mm^3) and CO_2 emissions (t CO_2e) for selected irrigated crops grown in the Mediterranean region.

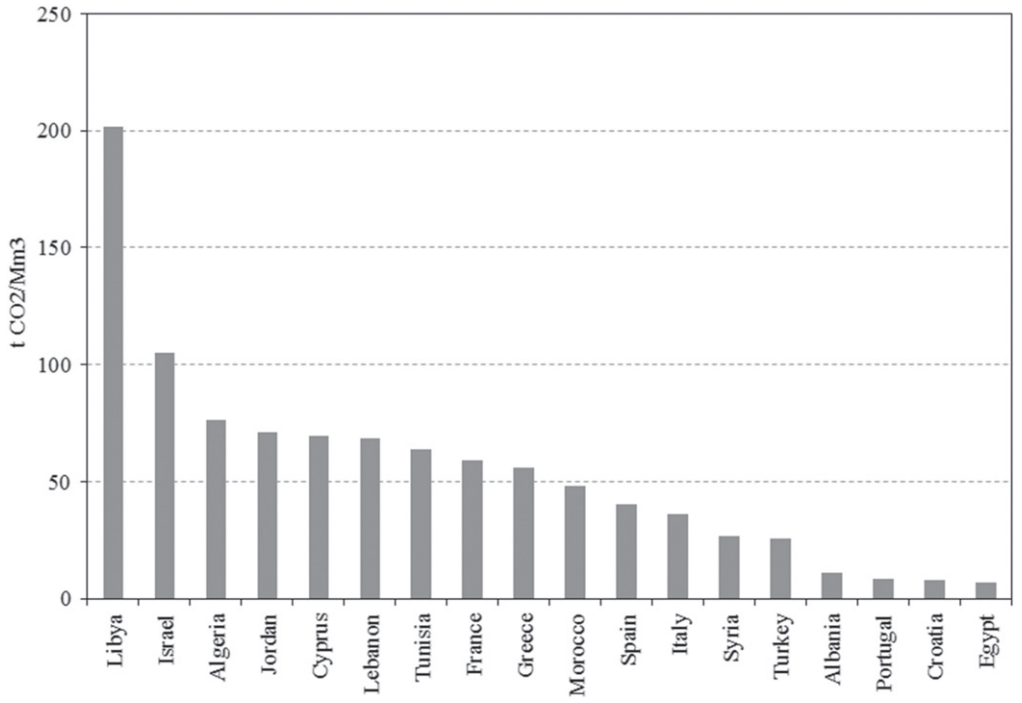

Figure 5. Estimated average CO_2 emissions per unit of water (t CO_2 Mm^{-3}) by country in the Mediterranean region.

analysis shows that Spain ranks highest in terms of energy demand for irrigation (>774 GW h) followed by Turkey (570 GW h) and Syria (529 GW h). Although irrigation demand in Egypt is 75% higher than Spain, its CO_2 emissions are three times lower (figure 4). This is due to the fact that Egypt relies heavily on surface irrigation (88%) which is gravity fed, and almost exclusively on the River Nile for its water source. Conversely, in Spain two thirds of the application systems used on-farm are pressurized (drip or sprinkler) and more than 20% of the irrigated area relies on ground water abstraction from deep aquifers (table 1). Syria and Turkey are also two major contributors to CO_2 emissions within the Mediterranean region as they have similar irrigation water demand (11 km^3) application methods and water sources (figure 4). Despite the relatively low water demand in Libya (1.4 km^3) it ranks fourth for CO_2 emissions from

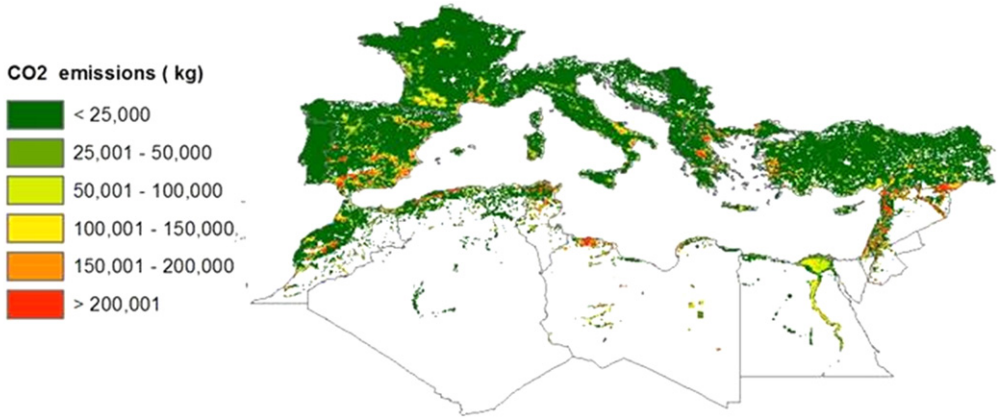

Figure 6. Estimated total carbon emissions (kg CO_2e) from irrigated agriculture across the Mediterranean region.

irrigated production (figure 4) and first per unit volume of water applied (figure 5). This is due to the fact that irrigation in Libya depends almost exclusively on groundwater (99%) and sprinklers (89%), which constitutes a high energy mix in irrigated production. In France, a large proportion of energy produced is derived from nuclear power; therefore even though the energy needed to apply 1 unit of water is higher than say Algeria, 17.4 t of additional CO_2 are emitted as Algerian energy is generated from fossil fuel. Countries such as Albania, Portugal and Egypt have the lowest energy needs and CO_2 emissions (<10 t CO_2 Mm^{-3}) since water for irrigation is pumped mainly from surface water and the uptake of high energy demanding pressurized irrigation systems is still very limited (figure 5). However, with growing pressure on food supplies driven by population growth and economic development, there could be major implications for both water and energy use in these countries.

3.3. Water demand and carbon emissions

Data on crop water needs and estimated CO_2 emissions for each crop type grown in the Mediterranean region have been combined and mapped (figure 6). Areas with the highest irrigation demand are concentrated in Southern Spain, South West France, the Po Valley and Apulia region in Italy, Western and South Eastern regions of Turkey, the Nile River Basin and the coastal areas of most Eastern and Southern Mediterranean countries. As the quantity of CO_2 emitted is directly related to the volume of water demanded, areas with the highest CO_2 emissions coincide with those having the highest water demand. Nationally, Spain, Syria and Turkey have the largest CO_2 emissions for irrigation (figure 4) whilst Libya, Israel and Algeria have the highest emissions per unit of water applied (figure 5).

Gassert *et al* (2013) produced a global water stress index which provides a spatial assessment of demand for freshwater from households, industry and irrigated agriculture, relative to freshwater availability in a typical year (figure 7(a)). High levels of baseline water stress indicate that demand for freshwater approaches (or exceeds) the annual renewable supply, which leads to greater socio-economic competition for freshwater and a higher risk of supply disruptions. When the volumetric water demand for key Mediterranean irrigated crops estimated in this study was combined with water stress index, nearly half (42%) the total water demand was found to be concentrated in river basins where the level of stress is already classified as 'extremely high' (>80% available water used); a further 17% of demand is located catchments designated as having a 'high' level of stress (80–40% of available water used). Only a small proportion (14%) of demand is located in regions where fresh water supplies are considered sustainable and sufficient to meet current and near term projected needs for households, industry and agriculture. This has major implications in terms of increasing future food production from irrigated agriculture under a changing climate.

Using crop production data and outputs from the modelling, the water productivity (t Mm^{-3}) and average carbon emissions (kg CO_2e/t) for each of the major crops in the Mediterranean region were estimated (figure 8). Water productivity is defined as the quantity of yield produced (tonne) for each unit of water applied (Mm^3). In this study, the volume of water applied was estimated from the theoretical crop water need and does not necessarily match the actual volume applied. For each tonne produced, sunflower has the highest CO_2 emission from irrigated production (73 kg CO_2e) followed by cotton (60 kg CO_2e) and olives (57 kg CO_2e). Citrus has a very high water productivity (3000 t Mm^{-3}) and represents the crop with the lowest CO_2 emissions for each tonne produced (figure 8). However, these values vary significantly between individual countries depending on local climate and reported levels of crop productivity (average yield).

3.4. Scenario analysis

Three scenarios were used to assess the implications of technological and environmental change on irrigation water demand and CO_2 emissions. These scenarios provide valuable insights of the potential impact of policy actions to support agricultural development and/or curb emissions. The baseline scenario assumes an irrigation demand in the Mediterranean region for key crops of 61.9 km^3 emitting 1.78 Gt CO_2e

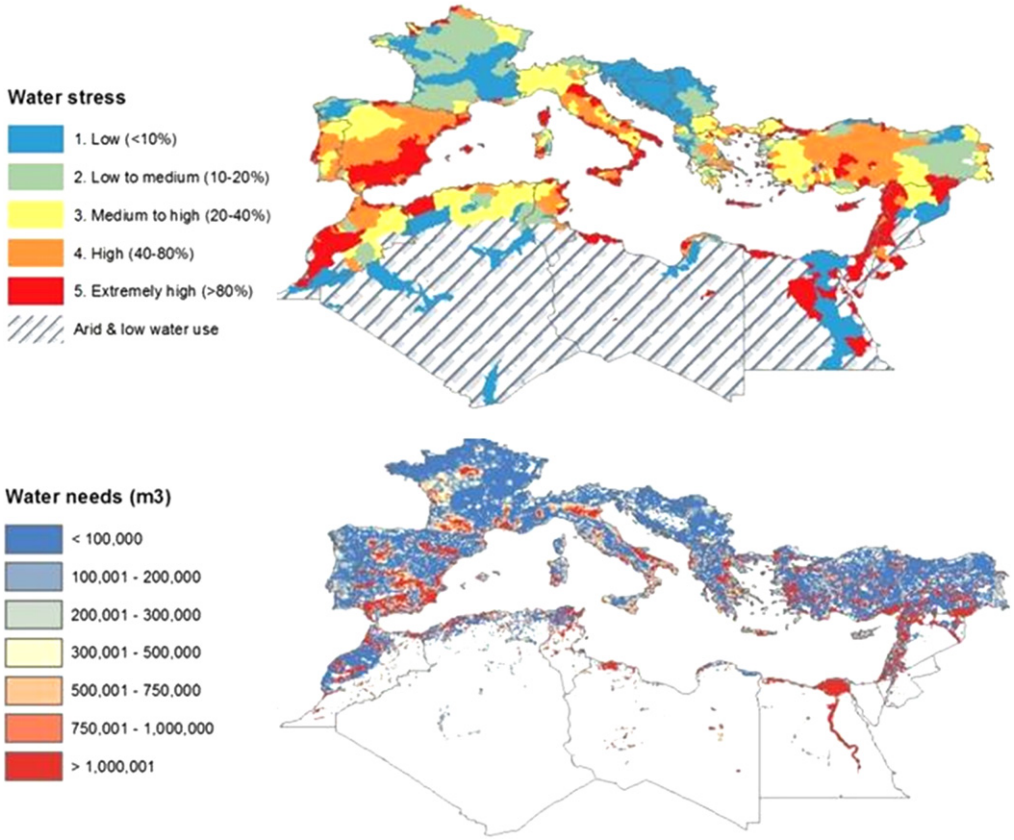

Figure 7. Water stress (Gassert *et al* 2013) (a) and volumetric irrigation water demand (m^3) (b) across the Mediterranean region.

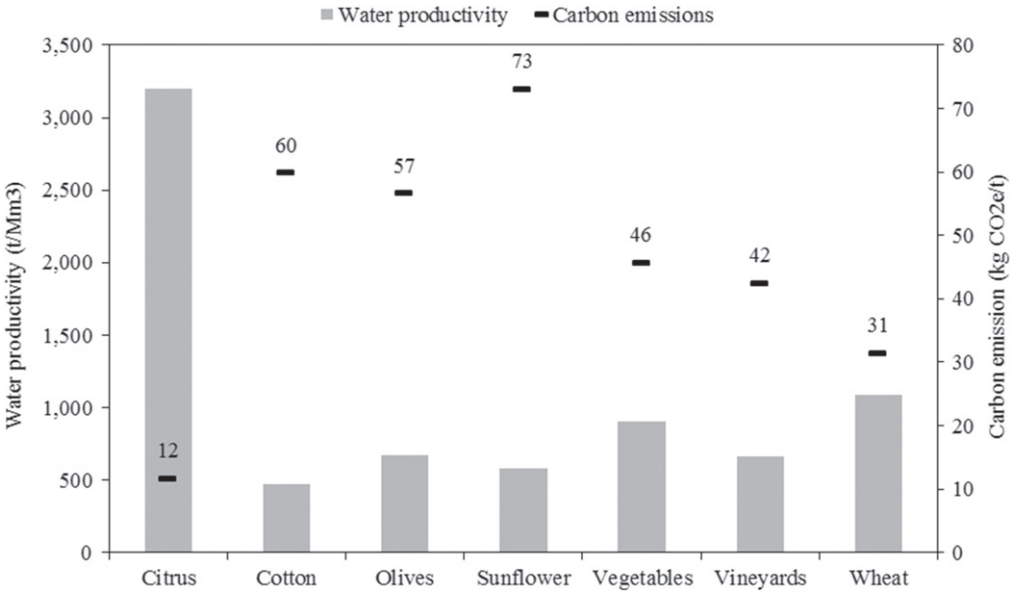

Figure 8. Estimated water productivity (t Mm^{-3}) and carbon emissions (kg CO_2e/t) for the major crop categories grown in the Mediterranean region.

(table 2). The first scenario reflects complete modernization of irrigated production via a switch from surface to pressurized (drip/sprinkler) systems. Theoretically, this scenario implies a water saving or reduction in water losses of 20–30%. The scenario assumes that the correct volume of water is applied at the right time regardless of the irrigation system and that water losses are caused by non-uniformity of application and evaporation. The type of pressurized system used is crop specific. For vegetables, cotton and sunflower where both drip and sprinkler systems are used, half the area irrigated with surface systems was assumed to convert to drip and the other half to sprinkler. Better application efficiency from

Table 2. Estimated change in water demand (Mm^3) and energy emissions (t CO_2e) from the current (baseline) for three alternative scenarios in Mediterranean irrigated agriculture.

	Baseline		Scenario				
			All pressurized		All irrigated		10 m fall GW level
Country	Water demand Mm^3	CO_2 emission t CO_2e	Water demand Mm^3	CO_2 emission t CO_2e	Water demand Mm^3	CO_2 emission t CO_2e	CO_2 emission t CO_2e
Albania	192	2752	161	7832	363	3938	2413
Algeria	1450	86 061	1227	163 889	6367	477 625	130 980
Bosnia & Herz.	2	133	2	194	360	30 302	207
Croatia	6	43	5	195	354	6395	55
Cyprus	57	2753	54	4661	117	7943	4608
Egypt	13 927	82 131	11 635	706 922	14 173	99 213	101 775
France	2213	156 223	2187	135 148	9651	567 829	140 824
Greece	1980	76 202	1832	123 654	7885	369 333	116 075
Israel	433	31 962	422	46 805	888	96 728	52 128
Italy	2936	92 276	2562	188 205	11 140	382 491	121 529
Jordan	405	22 126	385	35 067	2612	189 818	33 752
Lebanon	377	17 899	331	37 476	749	50 229	30 221
Libya	1391	174 095	1372	288 800	2 429	455 237	315 005
Macedonia	78	9193	78	13 049	164	27 231	14 680
Morocco	4224	140 437	3567	432 266	12 939	616 591	232 714
Portugal	318	2674	269	11 728	2,653	20 614	2685
Serbia & Mont.	142	13 724	142	19 956	998	157 212	23 025
Slovenia	1	47	1	50	5	312	55
Spain	7880	321 584	7289	429 843	28 509	1 062 314	343 503
Syria	11 050	220 096	9415	766 469	15 825	416 216	356 481
Tunisia	1568	83 314	1382	147 623	3941	248 635	119 191
Turkey	11 144	236 805	9347	627 080	40 623	1 020 774	328 658
West Bank	118	7641	111	12 500	3 041	279 918	12 429
Total	61 892	1 780 170	53 777	4 199 412	165 786	6 586 899	2 482 996

pressurized systems tends to reduce water losses but simultaneously tends to increase CO_2 emissions as more energy is needed for pumping. A scenario assuming a total switch from surface to pressurized systems shows a reduction in water demand of 8 km^3 (−13%) but an increase in CO_2 emissions of 2.42 Gt CO_2e (+135%). Most of the reduction in water use would occur in countries where a large proportion of existing agriculture depends on surface irrigation such as Egypt, Albania, Turkey, Morocco and Algeria (table 2). However, modernization would necessarily imply higher water costs that would lead to deficit irrigation in some crops (Rodríguez Díaz *et al* 2011) and also to a change in crop rotation to higher value crops with increased water requirements (Playán and Mateos 2006). These multiplicative effects were excluded from the analysis.

The second scenario assumed a fall in the water table depth by 10 m across the Mediterranean basin, which could occur if groundwater abstraction continued to exceed recharge. This is ongoing in the South and Eastern areas where over-exploitation of coastal groundwater has led to saltwater intrusion (Mediterra 2009). It has been estimated that 66% of unsustainable water use in the Mediterranean is currently derived from fossil water withdrawal, and this proportion is expected to increase in future driven by projected increases in water demand (Choukr-Allah *et al* 2012). This scenario assumes no change in the proportion of surface and groundwater sources used or in the existing cropping patterns and areas irrigated. The increase in CO_2 emissions was estimated to be 0.73 Gt CO_2e, above the current baseline, equivalent to an increase of 39% (table 2). This analysis assumes water quality remains unchanged and hence no additional volume of water is required for leaching of excess salt.

The final scenario assumed a switch from rain-fed to irrigated production to increase yield and quality and reduce the agro-economic impacts associated with increasing drought frequency. Assuming no change in the composition of land use would result in a +137% increase in water demand (166 km^3) with CO_2 emissions estimated to be 6.587 Gt CO_2e (+270%) (table 2). Although this scenario is unlikely due to physical water scarcity and economic limitations (water costs) there is evidence that switching from rain-fed to irrigated production is underway, largely in response to market demands for greater consistency and continuity of supply (Daccache *et al* 2012). It also highlights the high energy impact of policies aimed at increasing irrigated production.

3.5. Methodological limitations

Working at the regional scale necessitates compromises in spatial accuracy. This study used global datasets with each having its own level of inaccuracy. Previous research by Wisser *et al* (2008) reported a 30% variation in irrigation demand for the same region. Data on water sources and irrigation methods were derived from national statistics then averaged for each country. Although the use of national statistics is common in water footprint assessments (Hoekstra and Hung 2002), Montesinos *et al* (2011) highlight the differences of working at national level using a finer (farm) resolution which could be important in the Mediterranean region given small farm sizes. Crop types were chosen to represent the complex and diverse pattern of agricultural land use in the Mediterranean region. However, it is recognized that using representative crops in this way can mask important differences at the individual crop level, due to different growing seasons, water demands and target markets. Further research could investigate the sensitivity of using a limited number of crop types and extend the analysis to include a broader range of irrigated agricultural and non-food (bioenergy) crops.

Water demand was calculated assuming 'full' irrigation where the crop is grown under optimal soil moisture conditions. Sometimes full irrigation is restricted by physical constraints in water availability and often for economic reasons for certain drought tolerant crops (e.g. olives and cereals). Thus deficit irrigation on field crops is common practice in some parts of the Mediterranean region particularly in areas with high water costs (García-Vila *et al* 2008, Rodríguez Díaz *et al* 2011).

Unlike field-scale vegetables, cereals are considered low-value crops and hence full irrigation to avoid moisture stress free conditions throughout the growing season is not usually economically justified (Karrou and Oweis 2012). Supplemental irrigation is applied when dry spells coincide with the most crop sensitive periods to drought and heat stress (flowering and grain filling). This practice is commonly adopted in the Mediterranean region and in many part of the world on low value crops to minimize yield variation and maintain production to an economically acceptable level (Zhang *et al* 2004).Vegetable production under protected conditions (greenhouses) was not considered in this study. Compared to field-scale vegetable cropping, the productivity under such controlled environments can be higher with lower evaporative demand due to the noticeable reduction in solar radiation and lower wind speeds (Fernández *et al* 2007, Möller and Assouline 2007). Therefore, the reported values for water productivity of vegetables presented in this study could be higher than those actually obtained under greenhouse production. Water losses associated with inappropriate scheduling or poor management were also not considered but rather aggregated into fixed efficiency values for each irrigation method.

Due to a lack of published data, the sources of energy and proportional split between crops and application methods for pumping were estimated. However, the proportions assumed are likely to differ between countries and impact on CO_2 emissions. Finally, the water table depth was assumed to be constant which is not necessarily true in regions where abstraction dominates the summer period while recharge tends to occur in winter. Any effects of topography (differences in elevation from water source to irrigated area) were also excluded but could be important in steep irrigated areas such as in Spain (Navarro Navajas *et al* 2012). Other sources such as desalinated and recycled wastewater are also becoming important in coastal areas, and imply additional energy requirements that have not yet been evaluated.

4. Conclusions

This paper describes the first attempt to model, map and quantify the links between irrigation demand, crop production and energy consumption in Mediterranean irrigated agriculture. As water scarcity increases, agriculture is the focus of much attention to reduce water losses, improve efficiency and boost water productivity. In recent years, government subsidized pressurized irrigation systems have replaced traditional low efficiency surface irrigation schemes in many countries in an attempt to minimize water losses and improve efficiency. But the implications on energy use and carbon emissions have until now largely been ignored. In order to support the sustainable intensification of agriculture, particularly in the Mediterranean region, there will be a need for low cost, reliable, efficient irrigation systems that avoid excessive groundwater pumping supported by policies that recognize the trade-offs between saving water, reducing CO_2 emissions and intensifying food production.

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Water and energy footprint of irrigated agriculture in the Mediterranean region

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