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Cross-sectoral implications of the implementation of irrigation water use efficiency policies in Spain: A nexus footprint approach

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Abstract

One technical solution often suggested for alleviating water scarcity is to increase the efficiency of irrigation water use. In Spain, several plans have been launched since 2000 to upgrade irrigation infrastructures and thereby achieve water savings equivalent to 2,500 hm^3/year and promote rural development. The present study uses a footprint approach to evaluate the impacts on land, water, energy, and carbon emissions of the implementation of irrigation modernization policies in agriculture in Spain between 2005 and 2011. The results show that during the period studied, the irrigated area remained stable (+0.3%), although there was a shift in crop patterns, with low-value non-permanent crops being replaced by high-value permanent crops. The water demand for irrigation decreased by 21%; half of this is explained by the shift in crop patterns and the reduction of the consumptive fraction (i.e., blue water footprint), and the other half by the cutback of return flows associated with the higher efficiency of the irrigation infrastructure. Changes in water demand have been accompanied by a progressive substitution of surface water for groundwater. Reduced water demand for irrigation has brought a reduction of 13% in water's energy footprint and 21% in its carbon footprint. In relative terms, water efficiency (m^3 consumed/m^3 irrigated) has increased by 8%, although this has also increased the energy intensity (kWh/m^3) to 9%. The emission rate (KgCO$_2$ equiv./m^3 irrigated) has decreased by 12% as a result of the drop in the emission factor of electricity production. Overall, irrigation modernization policies in Spain have supported the transition from an irrigation sector that is less technified and heavily dependent on surface water into one that is more productive and groundwater-based. From a resource-use perspective, such transition has contributed to stabilizing or even decreasing the irrigated land, and surpass the annual water savings target of 2,500 hm^3, although it has also made the sector more energy-dependent. Despite the overall positive outcomes, the observed water savings are masked by various synergistic factors, including favorable climatological conditions toward the end of the study period, which contributed strongly to curbing overall irrigation water demand. In the light of the higher frequency of observed droughts in Spain, the investments done so far do not guarantee that the planned water saving targets can be sustained if not complemented with additional measures like restricting irrigated area and/or setting caps for water intensive crops.

Keywords: water footprint, energy footprint, carbon footprint, irrigation modernization, water scarcity, water-energy-food nexus, groundwater, surface water

Introduction

Water demand is increasing worldwide as a result of multiple drivers linked to urbanization, globalization, climate change, economic development and population growth (Cosgrove and Loucks, 2015; Hoekstra and Mekonnen, 2012; Mehram et al., 2017; Veldkamp et al., 2017; WWPA, 2016). As the most important global user of water (FAO, 2016; Gleick et al., 2014) agriculture lies at the core of many water disputes throughout the world (Llamas and Martínez-Santos, 2005; Molden et al., 2007). This is particularly true in arid and semi-arid regions, where the share of consumptive water use by irrigation easily reaches 90% (Hoekstra and Mekonnen, 2012).

In many arid and semi-arid regions, water scarcity is not just a growing environmental concern but also a structural problem (Berbel et al., 2015). During much of the 20th century, the prevailing approach to tackling water scarcity relied on the promotion of supply-oriented approaches, also called “hard-path” solutions (i.e., building infrastructures to secure availability) (Gleick, 2003). While this water management strategy has greatly contributed to improving water security in many regions, water demands have continued to rise, with many water systems approaching their physical boundaries. The need for a paradigm shift has promoted the development of so-called soft-path solutions or demand-driven approaches, and the focus is now on improving resource-use efficiency and strengthening water governance (Gleick, 2003; OECD, 2011).

From the resource management perspective, increasing water use efficiency is seen as a key strategy in terms of meeting current and future development needs, while at the same time reducing pressure on the environment (Dumont et al., 2013). Large investments have been devoted to this purpose, particularly in agriculture, to improve the “crop per drop.” However, the outcomes of water efficiency policies have not always led to net water savings (Grafton et al., 2018; Pfeiffer and Lin, 2014, Scheierling et al., 2006; Ward and Pulido-Vazquez, 2008), and have often generated unaccounted-for costs and impacts (Diaz et al., 2012). Spain is a paradigmatic case, being the most semi-arid country and the largest water consumer within the European Union (EUROSTAT, 2014). Irrigated agriculture in Spain accounts for 75% of national water consumption and is at the core of many regional water disputes (De Stefano and Llamas, 2012). Over the last decades, several policy measures have been implemented to ameliorate water scarcity and stress. The Spanish National Irrigation Plan (MAPA 2001a) and later the Shock Plan (2006–2008) (MARM 2006) are probably the most ambitious public initiatives implemented to date. The plans' overall purpose was to upgrade approximately 2.0 million ha of irrigated land, thereby saving 2,500 hm^3 of water annually, while strengthening the resilience and competitiveness of the Spanish agricultural sector (Lopez-Gunn et al., 2012). Despite there being no official ex post evaluation of this process, several studies were carried out in different basins to assess their outcomes in terms of water use and agricultural productivity. Dumont et al. (2013), Lecina et al. (2010), and Playan et al. (2006) confirmed the trend observed in other countries and regions for the Ebro basin in northeast Spain. They showed that although net agricultural water use did not reduce after the modernization process—and even slightly increased—the transformed areas saw significant increases in land productivity. As Dumont et al. (2013) described, increasing agricultural water use efficiency from a technical perspective might unintentionally lead to an overall aggregated increase in water consumption instead of the opposite, namely, the so-called rebound effect. This phenomenon, further explained and translated into numbers by Gómez and Gutiérrez (2011) and Gómez and Pérez-Blanco (2014), was also reported in the Guadalquivir basin (Berbel et al., 2013) and the Mediterranean region (Lorite et al., 2004).

The upgrading of irrigation infrastructures in Spain has been subsidized by public funds, but farmers also had to bear about 50% of the costs. To obtain returns on their investments, farmers might use the initial water "savings" to irrigate larger areas, and/or assume greater risks (i.e., by cultivating more profitable and more water-intensive crops or by intensifying crop rotations). All these decisions may offset any potential savings, and, at worst, increase overall water consumption at the basin scale. Berbel et al. (2015) showed that such a rebound effect in southern Spain was avoided to a large extent due to additional policy measures, including strict regulations limiting the expansion of irrigated land area. Likewise, water allocations were also revised in such a way that the water savings obtained were not reassigned to any economic use but returned into the system to improve the water balance and the environmental status of surface and groundwater bodies.

In addition to contested evaluations about actual net water savings, several authors have reported that increasing water use efficiency also has other unintended consequences like greater energy use

(Corominas, 2010; Rodriguez-Diaz et al., 2012; Soto-Garcia et al., 2013) and often a larger carbon footprint (Daccache et al., 2014).

Despite growing evidence on the trade-offs associated with increasing water use efficiency, much of the available literature on Spain either provides very context-specific examples or addresses the water–energy–food–carbon nexus on an almost bilateral basis, for example, water–energy and/or water–food links (e.g., Kuriqi et al., 2017, 2019; Martinez-Paz et al., 2018).

Accordingly, this paper aims to provide a comprehensive assessment of the implications linked to the modernization of irrigated infrastructures in Spain at national level from a resource-use perspective, including the use of water, land, energy, and carbon emissions. While this assessment is country-specific, the approach is transposable. The results are expected to contribute to the ongoing debate on the synergies and trade-offs linked to the promotion of technical measures to improve agricultural water use efficiency.

Methods

A footprint approach was applied to quantify the trends in water and energy consumption and carbon emissions linked to agricultural irrigation development in Spain. The temporal scale of analysis comprises the period 2005–2011, and the spatial unit of analysis are the administrative boundaries equivalent to provinces (NUTS3 in the nomenclature of territorial units for statistics within the EU) and the Autonomous Communities (NUTS2). The analysis focuses on irrigated croplands in the open air. Irrigated areas in greenhouses were excluded, as these are already considered as modernized irrigated areas and the margin for improving resource-use efficiency for this type of agriculture is limited. A summary of the methodological approach is presented in Figure 1, and a detailed description of the data and modeling approach is presented below.

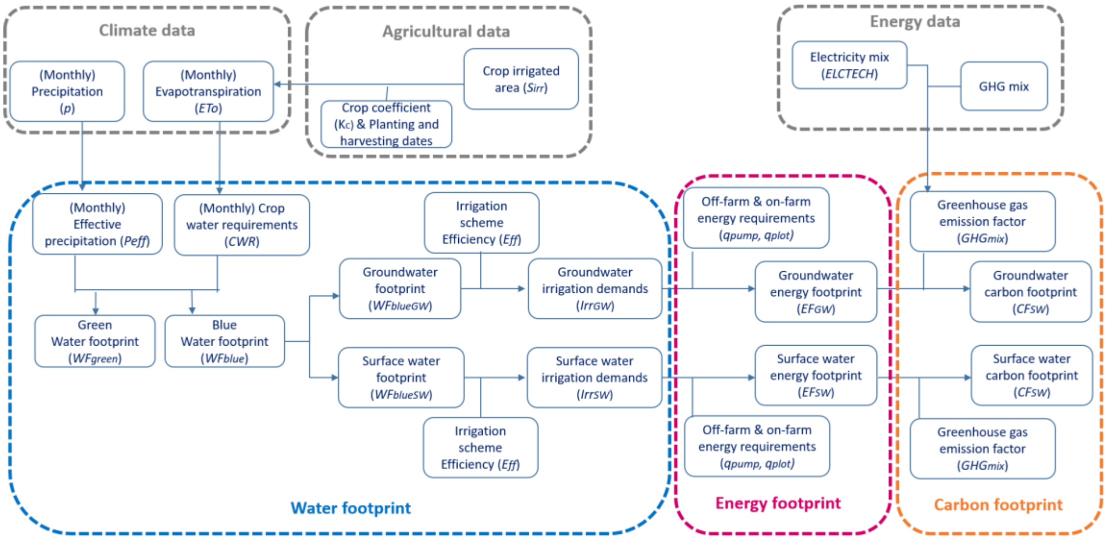

Figure 1. Methodological approach of the annual water, energy, and carbon footprint calculation

2.1 Water footprint

To quantify the annual consumptive use of water for irrigation we used the water footprint (*WF*) accounting methodology developed by Hoektra et al. (2011) and refined for the specific case of Spain by Garrido et al. (2011). The *WF* is here understood as the consumptive fraction of green (soil moisture) and blue water (surface and/or groundwater irrigation) embedded in the production of an agricultural crop. Accordingly, the annual *WF* of irrigated agriculture was estimated taking into account the total amount of green and blue water that is evapotranspired in year *i* by all open air irrigated areas.

$$WF_i\ (hm^3) = \sum_{j=1}^{49}\sum_{z=1}^{50}\left(WF_{green\ j,z} + WF_{blue\ j,z}\right) \qquad (1)$$

where WF_{green} (hm^3) represents the annual green water footprint of crop *j* and NUTS3 z and WF_{blue} (hm^3) is the annual blue water footprint. The *WF* analysis in this study was limited to the 49 most important irrigated crops in the open air (equivalent to 90% of the irrigated area in Spain in 2011) according to MAGRAMA (2015a).

The annual WF_{green} of a crop *j* in a NUTS3 *z* equals the sum of the monthly (*g*) effective precipitation (P_{eff}) during its cultivation period when the crop water requirements (*CWR*) are not met.

$$WF_{green\ i,j,z}\ (hm^3) = \sum_{g=1}^{n} \min(CWR_{j,z,g}\,; P_{eff\ z,g}) \times\ S_{irr\ i,j,z}\ \times 10^{-5} \qquad (2)$$

where S_{irr} (ha) is the irrigated area in year *i* and was obtained from the Yearly Agricultural Statistics of the Spanish Ministry of Agriculture (MAGRAMA, 2015a).

P_{eff} depends on the monthly precipitation (*p)* and was calculated using the formulae proposed by Brouwer and Heibloem (1986).

$$P_{eff\, z,g}\ (\mathrm{mm}) = 0.8 \times\ p_g - 25, if\ p_g > 75\ mm \qquad (3)$$

$$P_{eff\, z,g}\ (\mathrm{mm}) = 0.6 \times\ p_g - 10, if\ p_g < 75\ mm$$

CWR was estimated based on the reference evapotranspiration (ET_o) in month *g* and NUTS3 *z*, and the crop coefficient (K_c), which is the ratio of water requirements along the different growth stages.

$$CWR_{j,z,g}\ (mm) = \sum_{g=1}^{n} ET_{o\ z,g} \times\ K_{c\ j,g} \qquad (4)$$

Monthly values of *p* and ET_o (mm) were obtained from 50 meteorological stations (one per NUTS3) of the Spanish National Agency of Meteorology (AEMET, 2015) for the time series October 2005 until September 2011, and estimated using the approach by Penman-Monteith (Allen et al., 2006). Planting and harvesting dates were obtained from MAPA (2001b) and assumed to remain constant throughout the years. Appendix A summarizes the K_c values for the different growing stages (initial, development, mid-season, and end), and the planting and harvesting dates for the 49 irrigated crops under consideration.

The annual WF_{blue} was estimated as the sum of the volume of water needed when $CWR > P_{eff}$ during the cultivation period of crop *j* in NUTS3 *z*.

$$WF_{blue\ i,j,z}\ (hm^3) = \sum_{g=1}^{n} \max(0;\ CWR_{j,z,g} - P_{eff\ z,g}) \times\ S_{irr\ i,j,z}\ \times 10^{-5} \qquad (5)$$

The blue groundwater footprint ($WF_{blue\ GW}$) was estimated based on the annual groundwater use ratios ($ratio_{\ GW}$) obtained from the annual survey of agricultural water use for the period 2005–2011 (INE, 2012). As these ratios are provided at administrative units equivalent to NUTS2, it was assumed that in year *i* all crops cultivated in the different NUTS3 belonging to the same NUT2 (*k*) have the same $ratio_{\ GW}$. Appendix B summarizes the annual ratios of surface and groundwater use per NUTS2.

$$\mathrm{WF}_{blue\ GW\ i,j}\ (hm^3) = \sum_{k=1}^{17} WF_{blue\ i,j,z} \times\ ratio_{GW\ k,i} \qquad (6)$$

$$WF_{\ blue\ SW\ i,j}\ (hm^3) = \sum_{k=1}^{17} WF_{blue\ i,j,z} \times (1 - ratio_{GWk,i}) \qquad (7)$$

2.2 Energy footprint

The energy footprint (EF_i) computes the energy use associated with surface (EF_{SWi}) and groundwater (EF_{GWi}) irrigation along two steps: 1) withdrawal and pumping from the source (i.e. off-farm), and 2) irrigation within the plot (i.e. on-farm). Electricity was considered as the main source of energy, which is a reasonable assumption, as most irrigated systems in Spain have become almost completely dependent upon electricity (Corominas, 2010).

$$EF_i\ (\text{GWh}) = \sum_{j=1}^{49}\sum_{z=1}^{50}(EF_{SWi} + EF_{GWi}) = \sum_{j=1}^{49}\sum_{z=1}^{50}[\,Irr_{SWi,z,j} \times (q_{pump_{SW\,i,z}} + q_{plot\,i,z}) + Irr_{GW\,i,z,j} \times (q_{pump_{GW\,i,z}} + q_{plot\,i,z})\,] \qquad (8)$$

where Irr (hm^3) is the amount of water demand for irrigation, either from surface water (Irr_{SW}) or groundwater (Irr_{GW}), q_{pump} (kWh/m^3) is the average energy consumption from pumping and transportation of water i.e. off-farm energy cost and dependent on the source of water, and q_{plot} (kWh/m^3) is the energy demand for irrigation on-farm, and which depends only on the irrigation technology.

Irr was estimated based on the WF_{blue} by applying a loss coefficient equivalent to the inverse of the irrigation scheme's efficiency (Eff). Irrigation efficiency was estimated separately for surface (Eff_{SW}) and groundwater (Eff_{GW}), as a product of pumping and transportation efficiencies and plot irrigation efficiencies. Pumping and channel distribution efficiencies for each type of irrigation scheme were obtained as a mean of the average values reported by the River Basin Management Plans of the largest Spanish River basins, including the Ebro, Duero, and Guadalquivir (CHD, 2015; CHE, 2015; CHG, 2015). Plot irrigation efficiencies were estimated per year and NUTS3 as a weighted average of the irrigation efficiencies and area coverage per system σ (i.e., drip, sprinkling, automotive, and gravity). Appendix C provides a summary of the estimated efficiency values.

$$Irr_{SW\,i}\ (hm^3) = WF_{blue\,SW\,i} / Eff_{SW} \qquad (9)$$

$$Irr_{GW\,i}\ (hm^3) = WF_{blue\,GW\,i} / Eff_{GW} \qquad (10)$$

Where $WF_{blue\,SW}$ represents the volume of surface water from the total WF_{blue} and the $WF_{blue\,GW}$ equals the groundwater fraction. The annual return flows (RF_i) represent the irrigated water volume that is not evapotranspired and returns to the system.

$$RF_i\ (hm^3) = (Irr_{SWi} - WF_{blue\,SWi}) + (Irr_{GWi} - WF_{blue\,GWi}) \qquad (11)$$

q_{plot} was calculated taking into account the relative energy consumption (ω, kWh/m^3) of each irrigation system σ and the area ratio ($S_{\sigma,}$) each system occupies per NUTS3 and year. S_σ was obtained from the annual crop surveys (MAGRAMA, 2015b) and included in Appendix B. Table 1 summarizes the ω values used in the analysis.

$$q_{plot\ i,z}\ (kWh/m^3) = \sum_{\sigma=1}^{n} \omega_{\ plot\ \sigma} \times\ S_{\sigma,z,i} \tag{12}$$

Table 1. Mean energy consumption (*ω*, kWh/m^3) per irrigation system in Spain. Source: Corominas (2010)

Irrigation system	$\omega_{\text{ plot }\sigma}$	$\omega_{\text{ pump }\sigma}$
Gravity	0	0.02
Sprinkler and automotive	0.24	0.05
Drip	0.18	0.10

$q_{pump\ \mathrm{SW}}$ was estimated as a weighted average of the mean energy use linked to surface water pumping and transportation per irrigation system σ and the annual S_σ.

$$q_{pump\ SW\ i,z}\ (kWh/m^3) = \sum_{\sigma=1}^{n} \omega_{pump\ \sigma} \times\ S_{\sigma,z} \tag{13}$$

where ω_{pump} is the average energy consumption (kWh/m^3) associated with water withdrawal and transportation for an irrigation system σ (see Table 1).

$q_{pump\ \mathrm{GW}}$ was calculated based on the energy requirement to lift the water and following the method and assumptions proposed by Karimi et al. (2012). According to these authors, and based on Nelson and Robertson (2008), lifting 1000 m^3 water for 1 m at 100% efficiency, without considering friction losses requires 2.73 kWh. Accordingly, $q_{pump\ GW}$ we estimated as:

$$q_{pumpGWi,z}\ (kWh/m^3) = (2.73 \times D_{i,z}/(Eff_{pump}\ \times\ (1-TI) \times 1000) \tag{14}$$

where 2.73 represents unitary cost per meter depth (kWh/m), *D* is average pumping depth (m) per NUTS3 *z* and year *i*, Eff_{pump} is pump efficiency (%), and *TI* are pump transmission and distribution losses (%). Eff_{pump} was assumed to be 90% and *TI* losses established at 20%. Data on *D* was obtained from the official water bodies' qualitative state monitoring network (MAGRAMA, 2015c) and refers to the average annual water table depth per NUTS3. See Appendix D.

2.3 Carbon footprint

The carbon footprint (*CF*) calculates the emissions of greenhouse gases (GHGs) linked to the use of electricity for irrigating crops. Emissions linked to the building of the new irrigation infrastructures have not been considered, as they are regarded as negligible (Abrahao et al., 2017).

$$CF_i\ \ (kg\ CO_2\ equiv) = \sum_{j=1}^{49}\sum_{z=1}^{50}(EF_{SWi}\ + EF_{GWi})\ \ x\ GHG_{mix\ i} \tag{15}$$

where $GHG_{mix,}$ (kg CO_2 equiv./kWh) in year i is the greenhouse gas emission factor of the electricity production mix, and EF_{SW} and EF_{GW} are expressed in kWh. GHG_{mix} are calculated considering the composition of the electricity generation mix of technologies per year according to the following expression:

$$GHG_{mix\ i}(kg\ CO_2\ equiv./kWh) = \sum_{1}^{n} ELCTECH_{i,x} \times GHG_{i,x} \tag{16}$$

where $ELCTECH_{i,x}$ is the percentage contribution of each power generation technology x and GHG_i is the individual GHG emission rate of each technology in year i. $ELCTECH_{i,x}$ values were obtained from the annual reports of Spanish Electric Network (REE, 2006, 2012), the electricity production and transport system operator in Spain. Life Cycle Assessment (LCA) methodology was used to estimate the Carbon Footprint of each individual power technology contributing to the electricity generation mix. The Ecoinvent database (Frischknecht et al., 2005) was the source of the processes used to model each technology, with the general Ecoinvent datasets being adapted to the specific conditions of the Spanish mix. The Life Cycle Assessment software Simapro, a product of PRé Consultants (https://simapro.com/), was used to model the mix and estimate the aggregated GHG emissions. These emissions included the aggregated life cycle GHG emissions along the fuel chain and the emissions produced in the upstream (raw material extraction and production of components) and downstream stages (waste management). $GHG_{mix,i}$ values are summarized in Table 2.

Table 2. Evolution of the GHG emission factor of electricity production in Spain, 2005–2011 period. Source: own calculations.

Year	GHG emission rate GHG_{mix} (kg CO_2 equiv./kWh)
2005	0.457
2006	0.475
2007	0.481
2008	0.422
2009	0.382
2010	0.298
2011	0.398

2.4 Characterization of Spanish irrigated systems

We performed a multivariate analysis to understand the variability of irrigated crops across the territory, the temporal changes in the different crop footprints, and their correlation with a number of descriptive variables (see Appendix E). Specifically, we applied a factorial analysis (FA) using the Statistical Software XLSTAT 2017.4.45380 to reduce the dimensionality of the original matrix (24 variables x 56 observations corresponding to the 8 most irrigated NUTS2[1] for each of the 7 years) to

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[1] These 8 administrative units embrace 94% of the national irrigated area in both 2005 and 2011

a reduced number of factors or gradients that can explain the observed temporal and spatial variability of irrigated crops within Spain.

Results

Figure 2 summarizes the annual evolution of the *WF*, *EF*, and *CF* of irrigated crops between 2005 and 2011. Despite the relative stability of the irrigated area (2.85 million ha in 2005 and 2.86 million ha in 2011), the *WF* over the entire period decreased by 13.0% (17,134 hm^3 in 2005 to 14,903 hm^3 in 2011) (Figure 2a). The $WF_{\text{blue SW}}$ is the most important component of the total *WF*, but has decreased by 22.9% (12,784 hm^3 in 2005 to 9,855 hm^3 in 2011). This sharp decrease has been partly offset by a 7.0% rise in the $WF_{\text{blue GW}}$ (3,248 hm^3 in 2005 to 3,477 hm^3 in 2011) and by a 42.7% increase in the WF_{green} (1,101 hm^3 in 2005 to 1,572 hm^3 in 2011). The return flows also decreased by 26.6% (10,100 hm^3 in 2005 to 7,410 hm^3 in 2011).

The net reduction in the use and consumption of blue water for irrigation contributed to the 13.3% decrease in the *EF* (7,213 GWh in 2005 to 6,253 GWh in 2011) (Figure 2b). The EF_{SW} component decreased by 16.1% (3,913 GWh in 2005 to 3,282 GWh in 2011). Nevertheless, the unitary costs of pumping and irrigation on farm with surface water ($q_{pump\ SW}$ and $q_{plot\ SW}$) increased by 15% (0.18 KWh/m^3 in 2005 to 0.21 KWh/m^3 in 2011) (Table 3).

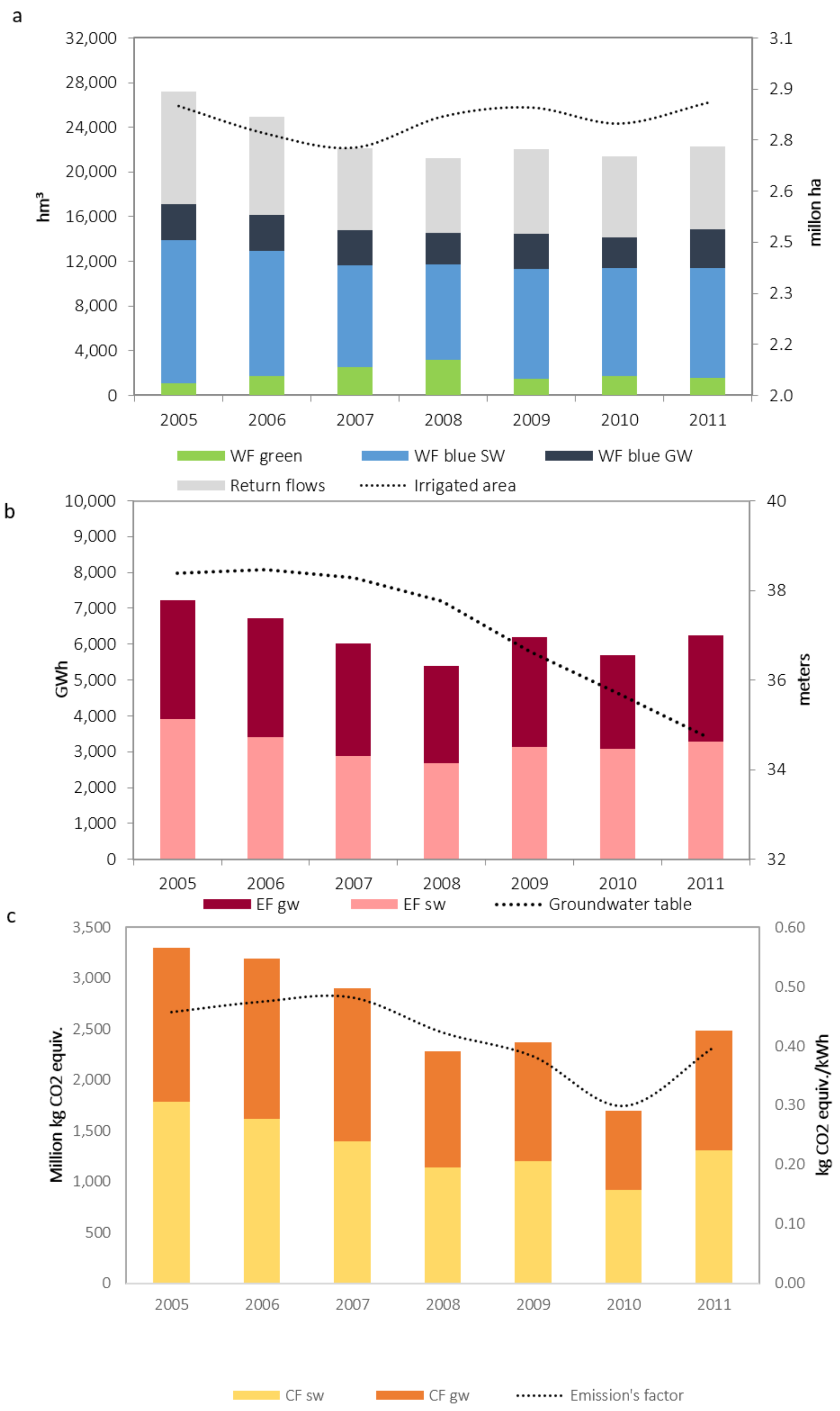

Figure 2. Annual water (a), energy (b), and carbon (c) footprints of Spanish irrigated agriculture.

The EF_{GW} reduced by 10.0% (3,300 GWh in 2005 to 2,971 GWh in 2011). The rise of the water table (Figure 2b) contributed to lowering the unitary groundwater pumping costs ($q_{pump\ GW}$) (Table 3), despite the overall increase in groundwater use. $q_{pump\ GW}$ accounted for up to 75% of the total energy costs linked to groundwater irrigation in 2011, and during the period analyzed, this variable reduced by 3.9%.

Table 3. Average unitary energy consumption associated with off-farm pumping and transportation (q_{pump}), and on-farm distribution and application(q_{plot}) stages for both surface and groundwater irrigation.

	Surface water			**Groundwater**		
	q_{pump} (kWh/m^3)	q_{plot} (kWh/m^3)	q_{pump} (% total)	q_{pump} (kWh/m^3)	q_{plot} (kWh/m^3)	q_{pump} (% total)
2005	0.06	0.12	31.9	0.59	0.15	78.9
2006	0.06	0.12	32.3	0.62	0.15	79.2
2007	0.06	0.13	32.1	0.56	0.16	78.8
2008	0.06	0.13	32.6	0.57	0.16	77.9
2009	0.06	0.13	32.7	0.58	0.16	78.1
2010	0.06	0.13	32.7	0.56	0.16	77.4
2011	0.07	0.14	32.3	0.48	0.16	75.0

The evolution of the *CF* also follows a downward trend (Figure 2c). Between 2005 and 2011, the *CF* decreased by 24.9%, (3,295 million kg (Mkg) of CO_2 equiv. in 2005 and 2,486 Mkg CO_2 equiv. in 2011). These emissions represent 0.8% of the total GHG emissions inventory for Spain, as reported by the Spanish Ministry for Agriculture and Fishing, Food, and Environment under the United Nations Framework Convention on Climate Change (MAPAMA, 2017). The cutback of the *CF* is due to the decrease of both fractions: the CF_{sw} decreased by 27%, while the CF_{gw} decreased by 21.6%.

Figure 3 shows how the *WF*, the *EF*, and the *CF* split among the different crop groups, and the changes between 2005 and 2011. Overall, crop groups belonging to the same typology (i.e., non-permanent and permanent crops) showed comparable footprint dynamics.[2]

From a water perspective, the largest share of the WF_{blueSW} in the two reference years was allocated to the cultivation of non-permanent crops, particularly cereals and industrial and fodder crops (Figure 3a). Over time, however, the WF_{blueSW} of non-permanent crops decreased overall by 48.2% (equivalent to an absolute reduction of -2,894 hm^3). On the other hand, the WF_{blueSW} of permanent crops remained stable between 2005 and 2011, with a net reduction of 0.9% (equivalent to -35 hm^3).

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[2] Non-permanent crops here include cereals, industrial, fodder, vegetables, and tubers; permanent crops refer to citrus and non-citrus trees, olive trees, and vineyards.

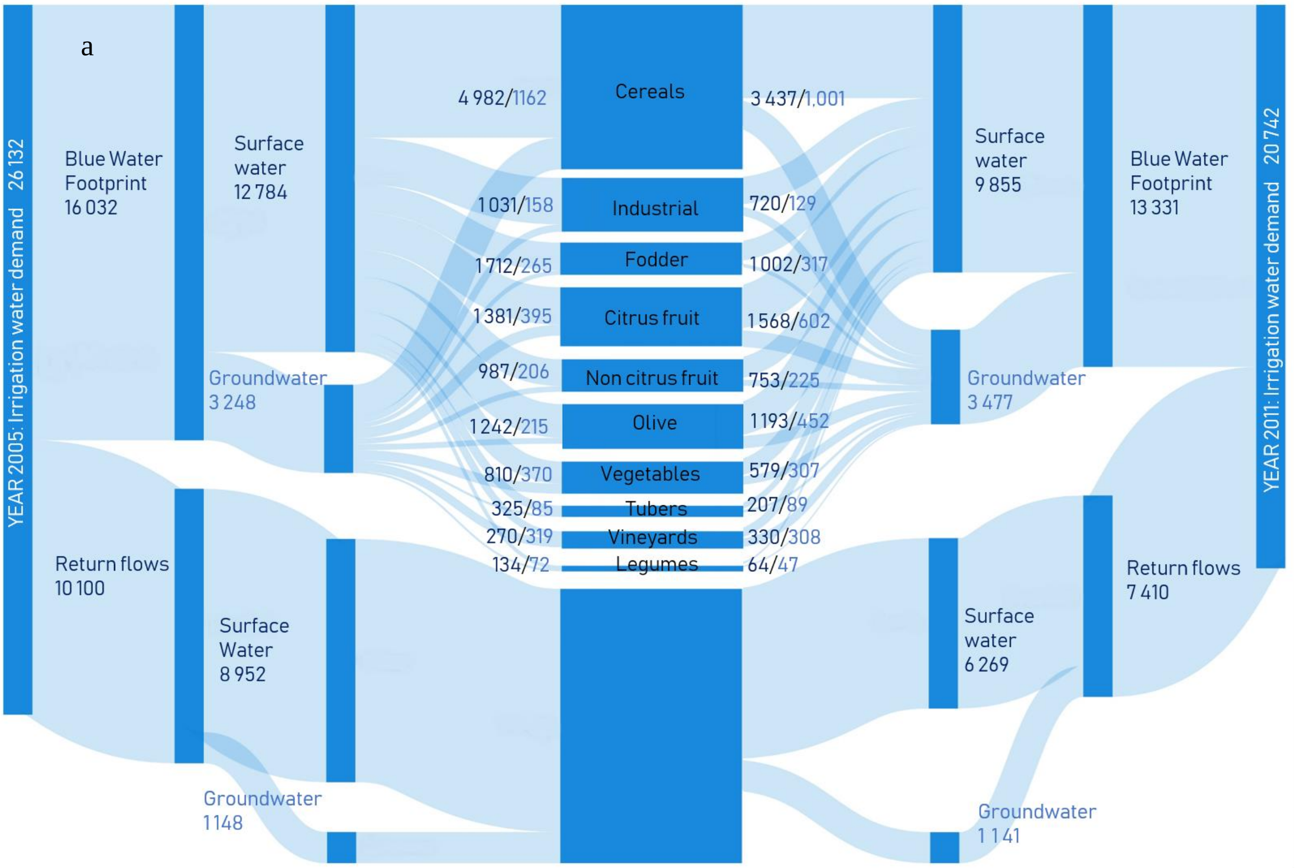
The largest share of the WF_{blueGW}, also relates to non-permanent crops. However, the aggregated WF_{blueGW} for non-permanents crops decreased by 11.8% (equivalent to -223 hm^3). This reduction is particularly due to the decrease in the WF_{blueGW} of cereals, and to a lesser extent, vegetables and fodder crops. On the other hand, the WF_{blueGW} of permanent crops raised overall by 28.5% (equivalent to a net increase of +452 hm^3), particularly because of the increased cultivation and irrigation of olive and citrus trees.

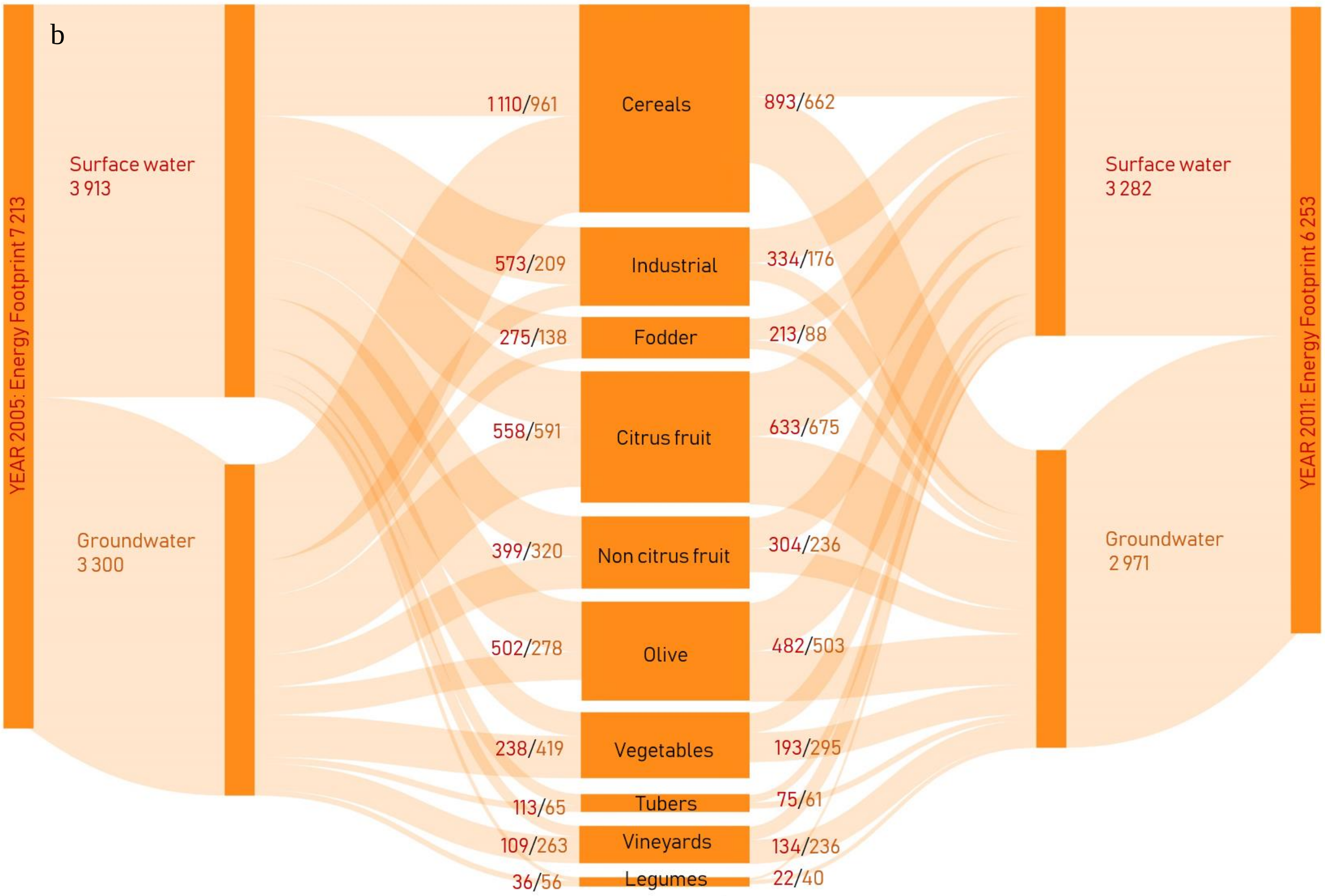
The largest fraction of return flows during the two reference years corresponds to RF_{SW}, and to a lesser extent to RF_{GW} (Figure 3a). Over time, the RF_{GW} remained stable, while the RF_{SW} decreased by 30% between 2005 and 2011.

The shifts in crop patterns and sources of water for irrigation also led to changes in the crops' *EF* (Figure 3b). The decrease in the irrigation of non-permanent crops translated into a 35.7% reduction of its EF_{BlueSW} (equivalent to -617 GWh), and a 39.8% decline in its EF_{BlueGW} (equivalent to -526 GWh). This downward trend is linked to the decreasing irrigation of cereals, industrial crops, and vegetables, and consequently of its surface and groundwater *EFs*.

The growing cultivation and irrigation of woody permanent crops with groundwater led to a 12.0% increase in its EF_{GW} (equivalent to +197 GWh). This increase is mainly due to the rise in the EF_{GW} of olive and citrus trees.

The *CF* follows a similar trend to that of the *EF*, although in the *CF* case a generalized decrease is observed for all crops and sources of water (Figure 3c). The CF_{SW} and CF_{GW} of non-permanent crops exhibits the largest changes, with a net reduction of 54.4% (equivalent to -395 million kg CO_2 equiv.), and 50.5% (equivalent to -306 million kg CO_2 equiv.). These sharp decreases are linked to the reduction of the CF_{SW} of cereals and industrial crops and, similarly, to the decline of the CF_{GW} of cereals and vegetables. With respect to the permanent crops, the CF_{SW} also decreased overall by 16.0% (equivalent to -99 million kg CO_2 equiv.), mainly as a result of non-citrus fruit and olive trees. The CF_{GW} of permanent crops remained stable with a net negative change equivalent to <1%.


a
YEAR 2005: Irrigation water demand 26 132
Blue Water Footprint 16 032
Return flows 10 100
Surface water 12 784
Groundwater 3 248
Surface Water 8 952
Groundwater 1148
4 982/1162
Cereals
3 437/1.001
1 031/158
Industrial
720/129
1 712/265
Fodder
1 002/317
1 381/395
Citrus fruit
1 568/602
987/206
Non citrus fruit
753/225
1 242/215
Olive
1 193/452
810/370
Vegetables
579/307
325/85
Tubers
207/89
270/319
Vineyards
330/308
134/72
Legumes
64/47
Surface water 9 855
Groundwater 3 477
Surface water 6 269
Groundwater 1 141
Blue Water Footprint 13 331
Return flows 7 410
YEAR 2011: Irrigation water demand 20 742


b
YEAR 2005: Energy Footprint 7 213
Surface water 3 913
Groundwater 3 300
1 110/961
Cereals
893/662
573/209
Industrial
334/176
275/138
Fodder
213/88
558/591
Citrus fruit
633/675
399/320
Non citrus fruit
304/236
502/278
Olive
482/503
238/419
Vegetables
193/295
113/65
Tubers
75/61
109/263
Vineyards
134/236
36/56
Legumes
22/40
Surface water 3 282
Groundwater 2 971
YEAR 2011: Energy Footprint 6 253

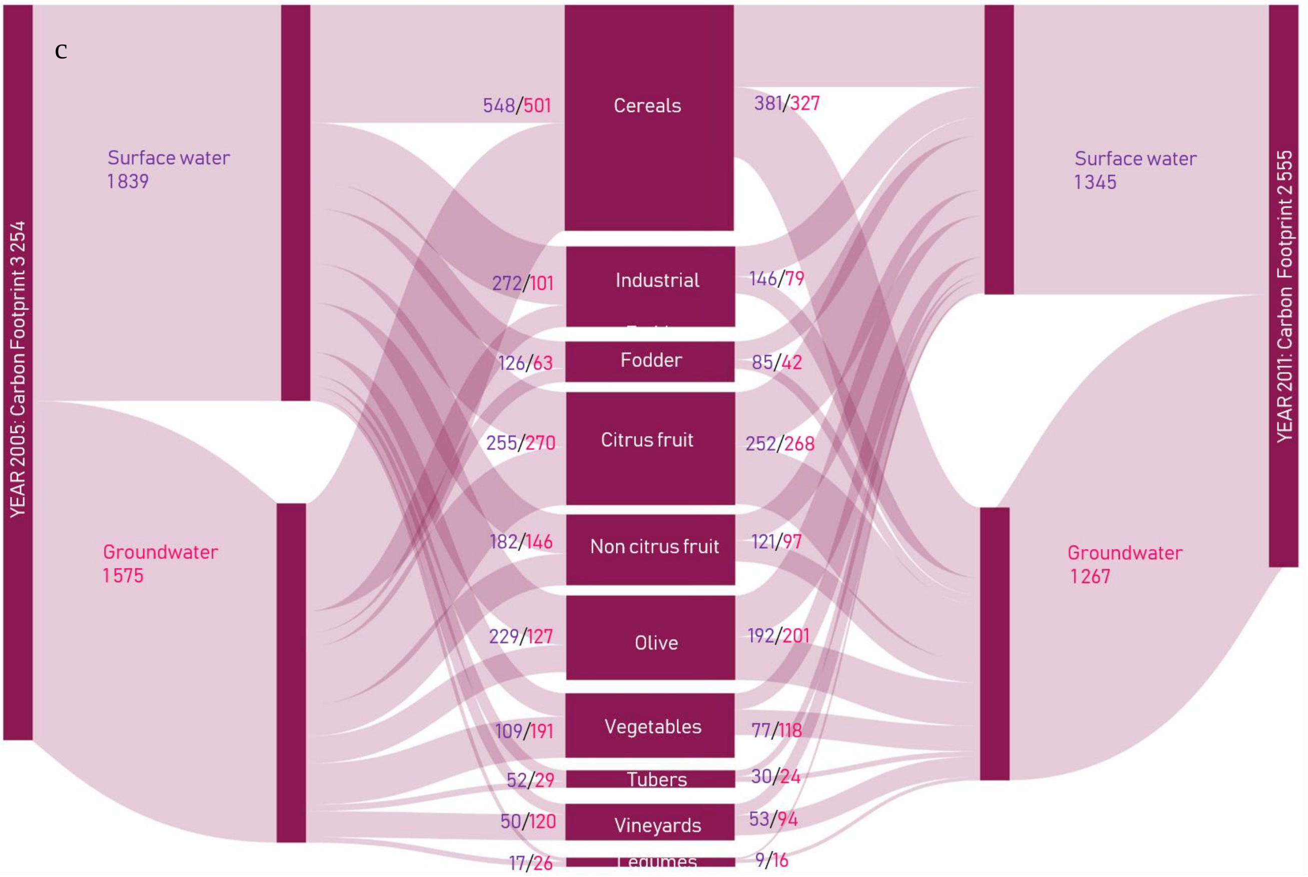


Figure 3. Surface and groundwater (a) blue water footprint (hm^3), (b) energy footprint (GWh), and (c) carbon footprint (million kg CO_2 equiv.) of the main irrigated crops in Spain in 2005 (left) and 2011 (right).

Alongside with the net changes in water, energy and emissions reduction, in the relative efficiencies have also experienced remarkable changes (Table 4). From a water perspective, the efficiency of irrigated agriculture has improved by 7.6%. However, the increase in water use efficiency has made the irrigation systems more energy-dependent, increasing the relative energy costs by 9.2%. From an emissions perspective, the emission rate follows the evolution of the emission intensity of the electricity production mix. This intensity increases, initially driven by an increasing penetration of combined cycle natural gas (with very high associated CH_4 emissions); it starts to decrease afterwards due to the penetration of renewable energies. The observed increment in the last period is due to the domestic coal promotion policy initiated in 2010. Overall, there was a reduction of 11.7% between the beginning and the end of the period analyzed.

Table 4. Efficiency rates in water, energy, and emissions of irrigated areas in Spain for the 2005–2011 period

	Water efficiency (m^3 consumed /m^3 irrigated)	Energy consumption (kWh/m^3 irrigated)	Emission rate (kg CO_2 equiv./m^3 irrigated)
2005	0.61	0.28	0.12
2006	0.62	0.29	0.15
2007	0.63	0.31	0.14
2008	0.64	0.30	0.13
2009	0.63	0.30	0.13
2010	0.63	0.29	0.10
2011	0.66	0.30	0.11

The results of the FA showed that the observed variability of Spanish irrigated agriculture can be described by two main factors (Figure 4): 1) the size of the irrigated schemes; and 2) the specialization in the production of crops and use of certain water sources. These two factors explain together 61.8% of the spatial and temporal variability observed.

Overall, the larger WF, EF, and CF are linked to the administrative regions with large irrigated schemes, that have experiencing the largest upgrades of their irrigation systems, and are highly specialized in the production of permanent crops and the use of groundwater (Figure 4, top right quadrant). These areas overlap with the southern half of Spain (i.e., the Andalusia and Castilla-La Mancha regions). The central and northern parts of the country (the Castilla y Leon region) also have large irrigated areas, albeit mostly devoted to the cultivation of non-permanent and low value crops that rely heavily on the use of surface water (bottom right quadrant). In the eastern and southeastern parts of Spain (the Murcia and Comunidad Valenciana regions), the irrigated area is moderate, but it is also highly specialized in the production of permanent crops (mostly citrus trees) and high added-value vegetables, heavily reliant on the use of groundwater (top left quadrant). The relative energy costs here (kWh/m^3) are among the highest in Spain. Other regions like Aragon, Extremadura, and Cataluña are less specialized, and the irrigated area is smaller in comparison with the neighboring administrative regions (bottom left quadrant). Lastly, it is important to highlight that the changes in irrigated areas and water demands observed between 2005 and 2011 have not altered the geographical specialization pattern across the country.

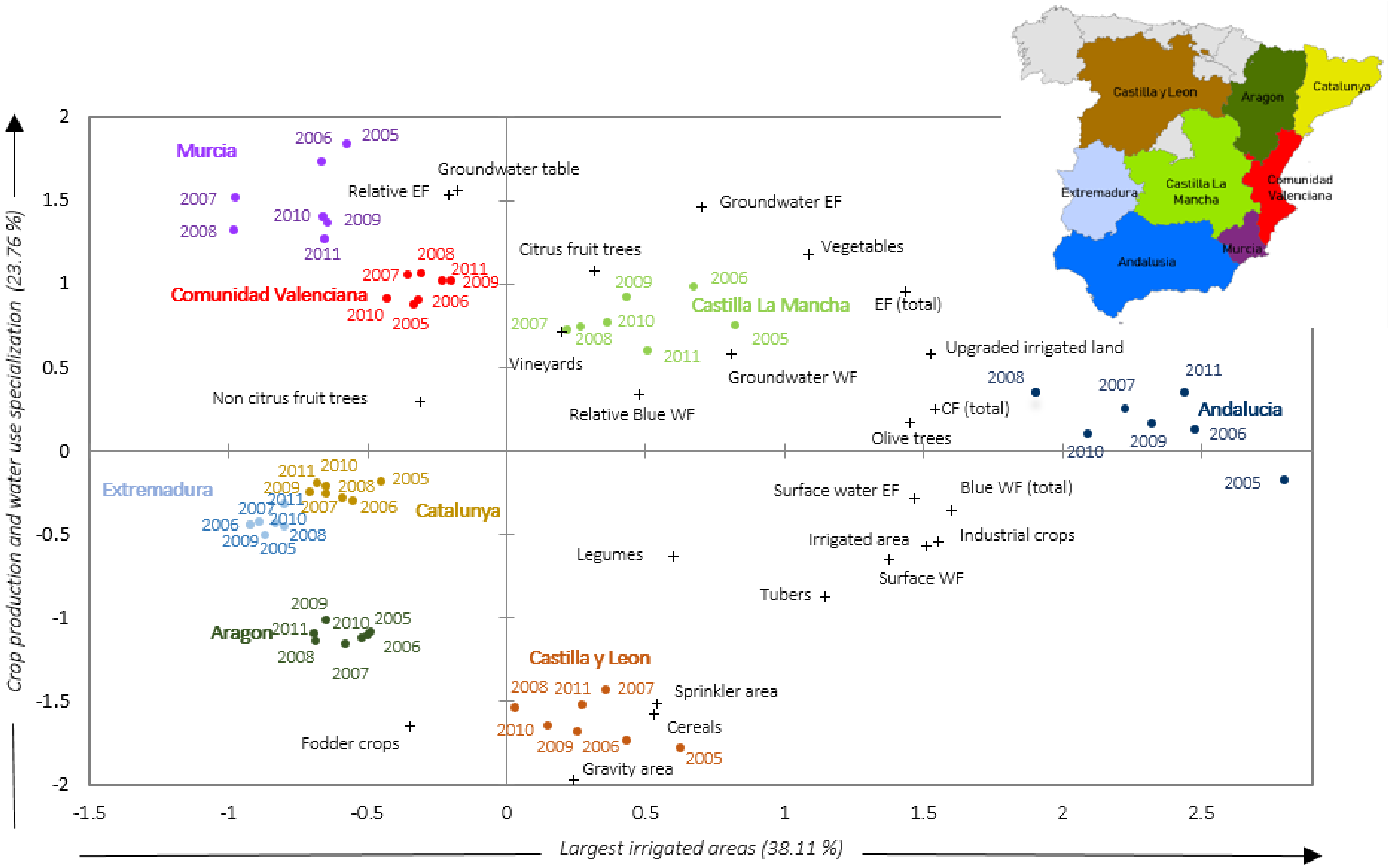


Figure 4. Factorial analysis describing the typology of major irrigation regions (NUTS2) in Spain and its linkage to the water, energy, and carbon footprints. Note: grey areas in the map represent regions with little irrigation development (overall representing <6% of the national irrigated area).

Discussion

The results of this study show that the water demand of irrigated agriculture in Spain (*Irr*) dropped by 21% between 2005 and 2011, which is equivalent to a net savings of 5,391 hm^3. The factors contributing to this reduction are diverse and cannot just be attributed to irrigation efficiency improvements. On the one hand, the consumptive use of blue water (WF_{blue}) decreased by 2,700 hm^3 mainly due to a reduction in harvested production (-1.1% with respect to 2005 levels) but, most importantly, due to the more favorable climate conditions and crop choices in 2011 (higher P_{eff} and lower *CWR*), which reduced the relative blue water footprint of crops by 9% (4,830 m^3/ha in 2005 and 4,380 m^3/ha in 2011). This confirms that, at the most, 50% of the achieved water savings (equivalent to 2,690 hm^3) can potentially be attributed to improvements in technical irrigation efficiency resulting from the replacement of the old open air channel distribution infrastructure by pressurization pipe networks. Under this scenario, the water savings resulting from improved efficiencies would have reached and actually surpassed the target of 2,500 hm^3/year set in the PNR-2008 (MAPA, 2001a), and the Shock Plan 2006–2008 (MARM, 2006).

Nevertheless, this hypothesis that it is efficiency improvements that have led to the met the targeted water savings cannot be confirmed. In fact, if the (dry) climate conditions of the year 2005 had prevailed in 2011, this would have led to a 9% decrease in the *Irr* (equivalent to net reduction of -2,344 hm^3). Under this scenario, net savings attributed to efficiency improvements would only have reached +1,800 hm^3. These findings are in line with other studies (i.e., Birkenholtz, 2017; Lopez-Gunn et al., 2012; Molle et al., 2017; Pfeiffer and Lin, 2014); and where it has been proved that water use efficiency policies have failed to achieve ambitious water savings targets and, in the worst case, to lead to an increase in water consumption.

Berbel et al. (2015) argued that water efficiency polices in areas suffering from over-allocation might deliver real water savings as long as they are accompanied by a number of additional measures, including: 1) a cap on the water extractions and on the further expansion of irrigated area; and 2) re-assignment of the water savings to the environment to release pressure on the system. In this respect, the results of our analysis show that between 2005 and 2011 the irrigated area remained fairly stable. Only a slight increase of +0.3% was registered due to an expansion of irrigated areas in the Comunidad Valenciana and Aragon regions, which was partly offset by the decrease experienced in some of the largest irrigated regions (Castilla-La Mancha and Castilla y Leon) (see Figure 4). Although the establishment of caps on water extractions cannot be tested, the results of our study show that the shift in crop patterns has in fact had a positive impact by driving the progressive replacement of water-intensive herbaceous crops (sugar beet, cotton, and maize) by high-value and less water-intense woody crops (particularly olive trees, citrus trees, and vineyards). According to our results, the average water demand per crop between 2005 and 2011 decreased by 14% (from 7,660 m^3/ha to 6,610 m^3/ha) and would have remained at 6% (from 7,660 m^3/ha to 7,220 m^3/ha) under constant climate conditions. The observed change in crop patterns confirms the results of Berbel et al. (2015) for southern Spain. However, it differs from other studies (i.e., Birkenholtz 2017 or Rodriguez-Diaz et al. 2011, 2012), who found that shifts in crop patterns actually led to more water-intensive production.

The shift toward high-value crops has also come at the expense of an increasing use of groundwater. This can be largely explained by the fact that groundwater is more resilient to climate variability (Calow et al., 2010) and that it is the preferred source of water for farmers in order to avoid risks and secure the production of high-value crops. As Figure 4 shows, the highest use of groundwater for irrigation is actually concentrated in the largest irrigated regions in Spain, namely, Andalusia, Castilla-La Mancha, Comunidad Valenciana, and Murcia, which are also the largest producers of cash crops. Some of these regions support the cultivation and export of berries and fresh vegetables, with apparent water productivities of €8.5/m^3 (Aldaya et al., 2010) and €7/m^3 (Dumont et al., 2011), respectively. As pointed out by De Stefano et al. (2014), groundwater in the period 2005–2008 generated at least 30% of the economic value of the national agricultural production of Spain, and this share is likely to keep growing because of the prevailing shift in crop patterns.

The upgrading of irrigated infrastructures has also had implications from an energy and emissions perspective. The overall decrease in the *EF* (-13%) is mainly related to the favorable climate conditions in 2011, which contributed to: 1) a decrease in the overall water demand (*Irr*); and 2) a reduction in the groundwater table depth, and consequently groundwater pumping costs ($q_{\text{pump GW}}$), which represented at least 75% of the energy bill during the analyzed period. Our estimates for $q_{\text{pump GW}}$ during the period analyzed show a slight decrease (0.59 kWh/m^3 in 2005 and 0.48 kWh/m^3 in 2011), and are slightly higher with the average value of 0.39 kWh/m^3 estimated by Corominas (2010). This difference might be attributed to the fact that the $q_{\text{pump GW}}$ calculation developed in this paper is sensitive to changes in the water table depth, which helps gain a more accurate estimate of price changes between dry and wet periods.

The literature on irrigation efficiency points to the fact that conversion into pressurized systems entails higher energy costs, and this is often the main driving factor motivating farmers to ultimately save water resources (Berbel et al., 2015; Rodriguez-Diaz et al., 2012; Soto-Garcia et al., 2013). Our study suggests that despite the overall decrease in the *EF*, the average unitary costs (kWh/m^3) at the national level have increased only moderately (Table 4). When looking separately at the unitary costs per irrigation system, surface water–dependent systems (EF_{sw}) have seen cost increases of 4% (0.21 kWh/m^3 to 0.22 kWh/m^3), whereas in groundwater-dependent systems the EF_{GW} has actually decreased by 7% (0.61 kWh/m^3 to 0.57 kWh/m^3). Once again, if the dry 2005 climate conditions had remained constant over the study period, the EF_{sw} and the EF_{GW} would have increased by 5% and 15%, respectively. While our results confirm an upward trend in the energy intensity of irrigated systems, the observed increase is fairly moderate compared with other assessments reporting energy costs increases above 70% (Jackson et al., 2010; Berbel et al., 2015).

From an emissions perspective, the reduction in the *CF* is greater than the overall *EF* decrease, and the dampening factor modulating this different behavior is the decreasing emission factor of electricity production from 0.46 kg CO_2 equiv./kWh in 2005 to 0.40 kg CO_2 equiv./kWh in 2011 (Figure 2c). This reduction is due to the mitigation policies implemented in the electricity sector with an increased penetration of renewable energies (11% in 2005 and 31% in 2011) in the electricity production mix of technologies in compliance with European Union targets (REE, 2006 and 2012).

The calculation of the *CF* relies on the assumption that electricity is the main source of energy for irrigation. This assumption seems reasonable for the early 2000s, when at least 73% of the energy for irrigation was provided by electricity and only 27% came from diesel pumps (Corominas, 2010). Published work on *CFs* in Spain (e.g., Bartzas et al., 2015; Martin-Gorriz et al., 2017), and in other countries such as India (Nelson et al., 2009; Shah, 2009) and China (Wang et al. 2012; Zou et al. 2015), has shown the important impact of the energy source used for water pumping on the *CF* of irrigation. Our results demonstrate that mitigation policies that reduce the *CF* of electricity generation have an important effect on the sustainability of agricultural irrigation. GHG emissions from irrigation represent only a small share of the emissions from agriculture. The size of this share depends on many factors including type of irrigation, source of water, and type of crop. Literature estimates range from an 8% share in northern areas of Spain in extensive cereal crops using surface water and modern irrigation systems (Abrahao et al., 2017), up to 35% in annual vegetable crops in the southeast of Spain using more than 50% of water from external transfers and almost 40% of groundwater. According to the latest energy and climate plans (PNIEC, 2019), the trend in the electricity sector is toward an 83% reduction in the carbon footprint of electricity generation in 2030 compared to 2005 and almost complete decarbonization in 2050. These future reductions in global warming emissions from electricity will enhance the observed downward tendency in the *CF* of Spanish irrigation.

Conclusions

This study shows that the irrigated sector in Spain has undergone an important transition in a relatively short period of time. From a less technology-based and heavily surface water–dependent agriculture it has moved toward being a modernized, more profitable and efficient one, that is also increasingly more reliant on groundwater.

From a resource-use perspective, the modernization of irrigated systems in Spain has contributed to increasing the production efficiency and reducing the energy and carbon footprints, although the efficiency gains are masked by a number of synergistic factors including favorable climate conditions and changes in the energy mix. While these later changes in the energy mix are the result of an overall transition toward a fully decarbonized sector by 2050 that will contribute to further increasing the sustainability of irrigated agriculture, the changing climate conditions, and particularly the risk of higher frequency of dry years, might compromise the positive outcomes of this water policy if not revised. The results of this assessment pinpoint to the fact that effective water policies should combine investments in irrigation infrastructures, with specific measures intended to set caps on the area that can be actually irrigated and/or the type of crops to be irrigated, particularly of water-intensive crops of low economic value.

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