

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

3 Barbara A. Willaarts,^{1,2*} Yolanda Lechón,³ Beatriz Mayor,^{1,2} Cristina de la Rúa,³ Alberto Garrido^{2,4}

4 ¹ International Institute of Applied System Analysis (IIASA), Laxenburg, Austria

5 ² Water Observatory-Botin Foundation, Madrid, Spain

6 ³ Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

7 ⁴ Research Center for the Management of Environmental and Agricultural Risks (CEIGRAM), Universidad Politécnica
8 de Madrid, Spain

9 *Corresponding author email: willaart@iiasa.ac.at; Address: Schlossplatz 1A, 2361 Laxenburg, Austria

10

11 **Abstract**

12 One technical solution often suggested for alleviating water scarcity is to increase the efficiency of
13 irrigation water use. In Spain, several plans have been launched since 2000 to upgrade irrigation
14 infrastructures and thereby achieve water savings equivalent to 2,500 hm³/year and promote rural
15 development. The present study uses a footprint approach to evaluate the impacts on land, water,
16 energy, and carbon emissions of the implementation of irrigation modernization policies in
17 agriculture in Spain between 2005 and 2011. The results show that during the period studied, the
18 irrigated area remained stable (+0.3%), although there was a shift in crop patterns, with low-value
19 non-permanent crops being replaced by high-value permanent crops. The water demand for
20 irrigation decreased by 21%; half of this is explained by the shift in crop patterns and the reduction
21 of the consumptive fraction (i.e., blue water footprint), and the other half by the cutback of return
22 flows associated with the higher efficiency of the irrigation infrastructure. Changes in water demand
23 have been accompanied by a progressive substitution of surface water for groundwater. Reduced
24 water demand for irrigation has brought a reduction of 13% in water's energy footprint and 21% in
25 its carbon footprint. In relative terms, water efficiency (m³ consumed/m³ irrigated) has increased by
26 8%, although this has also increased the energy intensity (kWh/m³) to 9%. The emission rate
27 (KgCO₂ equiv./m³ irrigated) has decreased by 12% as a result of the drop in the emission factor of
28 electricity production. Overall, irrigation modernization policies in Spain have supported the
29 transition from an irrigation sector that is less technified and heavily dependent on surface water into
30 one that is more productive and groundwater-based. From a resource-use perspective, such transition
31 has contributed to stabilizing or even decreasing the irrigated land, and surpass the annual water
32 savings target of 2,500 hm³, although it has also made the sector more energy-dependent. Despite the
33 overall positive outcomes, the observed water savings are masked by various synergistic factors,

34 including favorable climatological conditions toward the end of the study period, which contributed
35 strongly to curbing overall irrigation water demand. In the light of the higher frequency of observed
36 droughts in Spain, the investments done so far do not guarantee that the planned water saving targets
37 can be sustained if not complemented with additional measures like restricting irrigated area and/or
38 setting caps for water intensive crops.

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

41

42 **Introduction**

43 Water demand is increasing worldwide as a result of multiple drivers linked to urbanization,
44 globalization, climate change, economic development and population growth (Cosgrove and Loucks,
45 2015; Hoekstra and Mekonnen, 2012; Mehram et al., 2017; Veldkamp et al., 2017; WWPA, 2016).
46 As the most important global user of water (FAO, 2016; Gleick et al., 2014) agriculture lies at the
47 core of many water disputes throughout the world (Llamas and Martínez-Santos, 2005; Molden et
48 al., 2007). This is particularly true in arid and semi-arid regions, where the share of consumptive
49 water use by irrigation easily reaches 90% (Hoekstra and Mekonnen, 2012).

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

59 From the resource management perspective, increasing water use efficiency is seen as a key strategy
60 in terms of meeting current and future development needs, while at the same time reducing pressure
61 on the environment (Dumont et al., 2013). Large investments have been devoted to this purpose,
62 particularly in agriculture, to improve the “crop per drop.” However, the outcomes of water
63 efficiency policies have not always led to net water savings (Grafton et al., 2018; Pfeiffer and Lin,
64 2014, Scheierling et al., 2006; Ward and Pulido-Vazquez, 2008), and have often generated

65 unaccounted-for costs and impacts (Diaz et al., 2012). Spain is a paradigmatic case, being the most
66 semi-arid country and the largest water consumer within the European Union (EUROSTAT, 2014).
67 Irrigated agriculture in Spain accounts for 75% of national water consumption and is at the core of
68 many regional water disputes (De Stefano and Llamas, 2012). Over the last decades, several policy
69 measures have been implemented to ameliorate water scarcity and stress. The Spanish National
70 Irrigation Plan (MAPA 2001a) and later the Shock Plan (2006–2008) (MARM 2006) are probably
71 the most ambitious public initiatives implemented to date. The plans' overall purpose was to upgrade
72 approximately 2.0 million ha of irrigated land, thereby saving 2,500 hm³ of water annually, while
73 strengthening the resilience and competitiveness of the Spanish agricultural sector (Lopez-Gunn et
74 al., 2012). Despite there being no official ex post evaluation of this process, several studies were
75 carried out in different basins to assess their outcomes in terms of water use and agricultural
76 productivity. Dumont et al. (2013), Lecina et al. (2010), and Playan et al. (2006) confirmed the trend
77 observed in other countries and regions for the Ebro basin in northeast Spain. They showed that
78 although net agricultural water use did not reduce after the modernization process—and even slightly
79 increased—the transformed areas saw significant increases in land productivity. As Dumont et al.
80 (2013) described, increasing agricultural water use efficiency from a technical perspective might
81 unintentionally lead to an overall aggregated increase in water consumption instead of the opposite,
82 namely, the so-called rebound effect. This phenomenon, further explained and translated into
83 numbers by Gómez and Gutiérrez (2011) and Gómez and Pérez-Blanco (2014), was also reported in
84 the Guadalquivir basin (Berbel et al., 2013) and the Mediterranean region (Lorite et al., 2004).

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

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

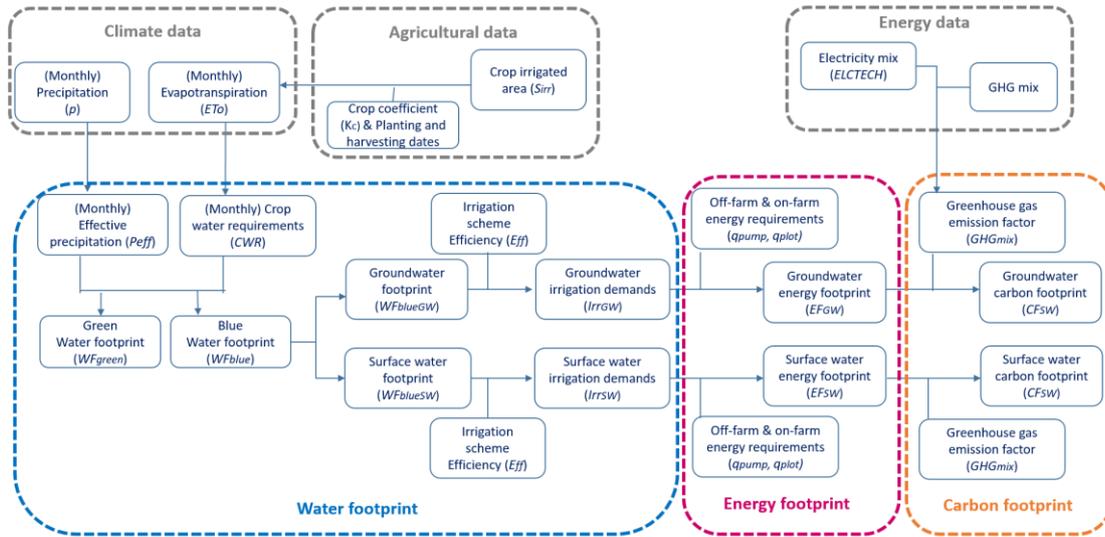
97 (Corominas, 2010; Rodriguez-Diaz et al., 2012; Soto-Garcia et al., 2013) and often a larger carbon
98 footprint (Daccache et al., 2014).

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

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

109 **Methods**

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



119

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

121 2.1 Water footprint

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

$$129 \quad WF_i \text{ (} hm^3 \text{)} = \sum_{j=1}^{49} \sum_{z=1}^{50} (WF_{green\ j,z} + WF_{blue\ j,z}) \quad (1)$$

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

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

$$136 \quad WF_{green\ i,j,z} \text{ (} hm^3 \text{)} = \sum_{g=1}^n \min(CWR_{j,z,g}; P_{eff\ z,g}) \times S_{irr\ i,j,z} \times 10^{-5}$$

137 (2)

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

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

$$142 P_{effz,g} \text{ (mm)} = 0.8 \times p_g - 25, \text{ if } p_g > 75 \text{ mm} \quad (3)$$

$$143 P_{effz,g} \text{ (mm)} = 0.6 \times p_g - 10, \text{ if } p_g < 75 \text{ mm}$$

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

$$146 CWR_{j,z,g} \text{ (mm)} = \sum_{g=1}^n ET_{o,z,g} \times K_{c,j,g} \quad (4)$$

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

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

$$156 WF_{blue\ i,j,z} \text{ (hm}^3\text{)} = \sum_{g=1}^n \max(0; CWR_{j,z,g} - P_{eff\ z,g}) \times S_{irr\ i,j,z} \times 10^{-5} \quad (5)$$

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

$$163 WF_{blue\ GW\ i,j} \text{ (hm}^3\text{)} = \sum_{k=1}^{17} WF_{blue\ i,j,z} \times ratio_{GW\ k,i} \quad (6)$$

$$164 WF_{blue\ SW\ i,j} \text{ (hm}^3\text{)} = \sum_{k=1}^{17} WF_{blue\ i,j,z} \times (1 - ratio_{GW\ k,i}) \quad (7)$$

165 2.2 Energy footprint

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

$$171 \quad EF_i \text{ (GWh)} = \sum_{j=1}^{49} \sum_{z=1}^{50} (EF_{SWi} + EF_{GWi}) = \sum_{j=1}^{49} \sum_{z=1}^{50} [Irr_{SWi,z,j} \times (q_{pump_{SW\ i,z}} + q_{plot\ i,z}) +$$

$$172 \quad Irr_{GWi,z,j} \times (q_{pump_{GW\ i,z}} + q_{plot\ i,z})] \quad (8)$$

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

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

$$187 \quad Irr_{SWi} \text{ (} hm^3 \text{)} = WF_{blue\ SWi} / Eff_{SW} \quad (9)$$

$$188 \quad Irr_{GWi} \text{ (} hm^3 \text{)} = WF_{blue\ GWi} / Eff_{GW} \quad (10)$$

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

$$192 \quad RF_i \text{ (} hm^3 \text{)} = (Irr_{SWi} - WF_{blue\ SWi}) + (Irr_{GWi} - WF_{blue\ GWi}) \quad (11)$$

193 q_{plot} was calculated taking into account the relative energy consumption (ω , kWh/m^3) of each
 194 irrigation system σ and the area ratio (S_{σ}) each system occupies per NUTS3 and year. S_{σ} was

195 obtained from the annual crop surveys (MAGRAMA, 2015b) and included in Appendix B. Table 1
 196 summarizes the ω values used in the analysis.

$$197 \quad q_{plot\ i,z} (kWh/m^3) = \sum_{\sigma=1}^n \omega_{plot\ \sigma} \times S_{\sigma,z,i} \quad (12)$$

198 **Table 1. Mean energy consumption (ω , kWh/m³) per irrigation system in Spain.** Source:
 199 Corominas (2010)

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

200 $q_{pump\ SW}$ was estimated as a weighted average of the mean energy use linked to surface water
 201 pumping and transportation per irrigation system σ and the annual S_{σ} .

$$202 \quad q_{pump\ SW\ i,z} (kWh/m^3) = \sum_{\sigma=1}^n \omega_{pump\ \sigma} \times S_{\sigma,z} \quad (13)$$

203 where ω_{pump} is the average energy consumption (kWh/m³) associated with water withdrawal and
 204 transportation for an irrigation system σ (see Table 1).

205 $q_{pump\ GW}$ was calculated based on the energy requirement to lift the water and following the method
 206 and assumptions proposed by Karimi et al. (2012). According to these authors, and based on Nelson
 207 and Robertson (2008), lifting 1000 m³ water for 1 m at 100% efficiency, without considering friction
 208 losses requires 2.73 kWh. Accordingly, $q_{pump\ GW}$ we estimated as:

$$209 \quad q_{pump\ GW\ i,z} (kWh/m^3) = (2.73 \times D_{i,z} / (Eff_{pump} \times (1 - TI) \times 1000)) \quad (14)$$

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

215 **2.3 Carbon footprint**

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

$$219 \quad CF_i (kg\ CO_2\ equiv) = \sum_{j=1}^{49} \sum_{z=1}^{50} (EF_{SWi} + EF_{GWi}) \times GHG_{mix\ i} \quad (15)$$

220 where GHG_{mix} , (kg CO₂ equiv./kWh) in year i is the greenhouse gas emission factor of the electricity
 221 production mix, and EF_{SW} and EF_{GW} are expressed in kWh. GHG_{mix} are calculated considering the
 222 composition of the electricity generation mix of technologies per year according to the following
 223 expression:

$$224 \quad GHG_{mix\ i} (kg\ CO_2\ equiv./kWh) = \sum_1^n ELCTECH_{i,x} \times GHG_{i,x} \quad (16)$$

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

237 **Table 2. Evolution of the GHG emission factor of electricity production in Spain, 2005–2011**
 238 **period.** Source: own calculations.
 239

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

240 2.4 Characterization of Spanish irrigated systems

241 We performed a multivariate analysis to understand the variability of irrigated crops across the
 242 territory, the temporal changes in the different crop footprints, and their correlation with a number of
 243 descriptive variables (see Appendix E). Specifically, we applied a factorial analysis (FA) using the
 244 Statistical Software XLSTAT 2017.4.45380 to reduce the dimensionality of the original matrix (24
 245 variables x 56 observations corresponding to the 8 most irrigated NUTS2¹ for each of the 7 years) to

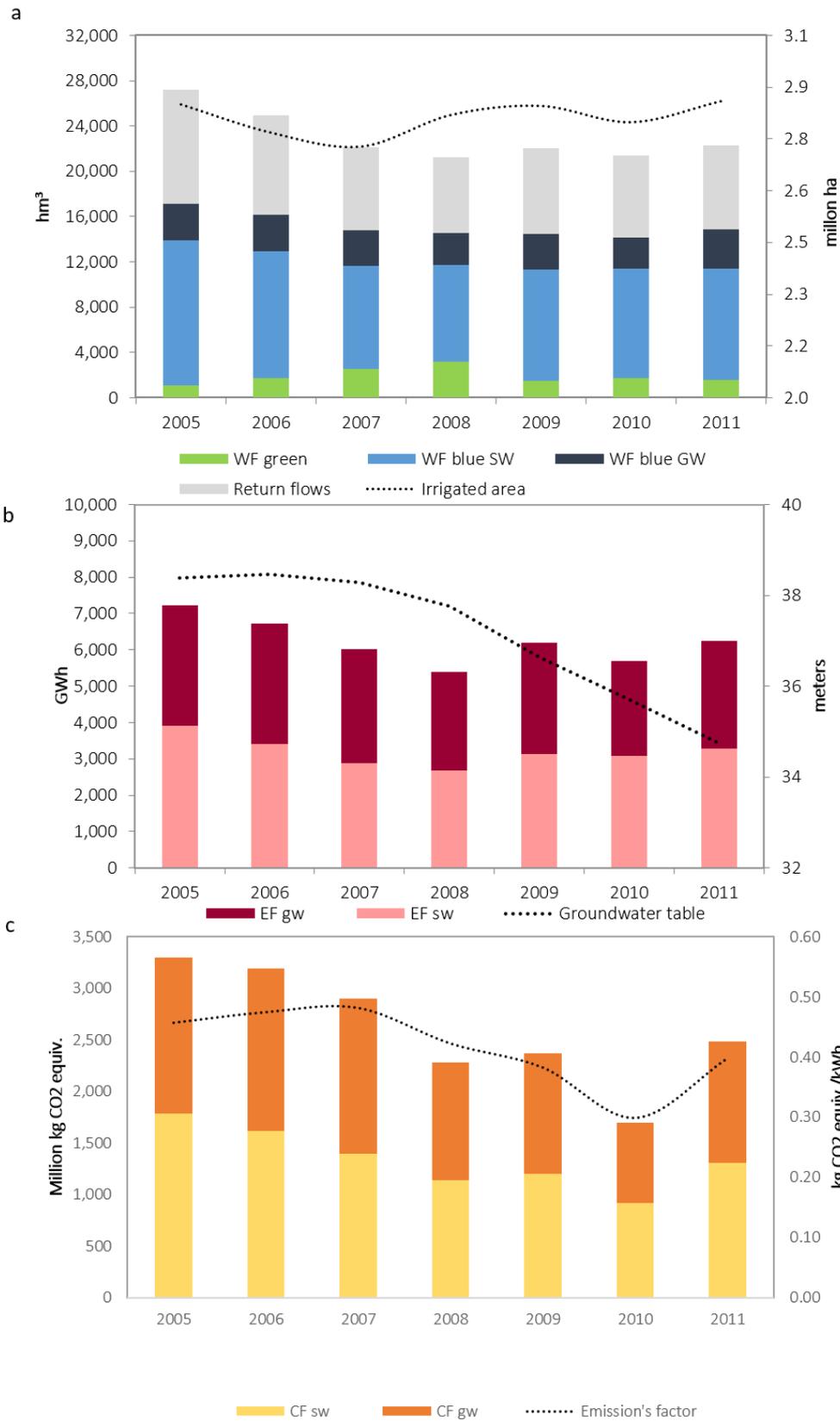
¹ These 8 administrative units embrace 94% of the national irrigated area in both 2005 and 2011

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

248 **Results**

249 Figure 2 summarizes the annual evolution of the WF , EF , and CF of irrigated crops between 2005
250 and 2011. Despite the relative stability of the irrigated area (2.85 million ha in 2005 and 2.86 million
251 ha in 2011), the WF over the entire period decreased by 13.0% (17,134 hm³ in 2005 to 14,903 hm³ in
252 2011) (Figure 2a). The $WF_{\text{blue SW}}$ is the most important component of the total WF , but has
253 decreased by 22.9% (12,784 hm³ in 2005 to 9,855 hm³ in 2011). This sharp decrease has been partly
254 offset by a 7.0% rise in the $WF_{\text{blue GW}}$ (3,248 hm³ in 2005 to 3,477 hm³ in 2011) and by a 42.7%
255 increase in the WF_{green} (1,101 hm³ in 2005 to 1,572 hm³ in 2011). The return flows also decreased by
256 26.6% (10,100 hm³ in 2005 to 7,410 hm³ in 2011).

257 The net reduction in the use and consumption of blue water for irrigation contributed to the 13.3%
258 decrease in the EF (7,213 GWh in 2005 to 6,253 GWh in 2011) (Figure 2b). The EF_{SW} component
259 decreased by 16.1% (3,913 GWh in 2005 to 3,282 GWh in 2011). Nevertheless, the unitary costs of
260 pumping and irrigation on farm with surface water ($q_{\text{pump SW}}$ and $q_{\text{plot SW}}$) increased by 15% (0.18
261 KWh/m³ in 2005 to 0.21 KWh/m³ in 2011) (Table 3).



262

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

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

270 **Table 3. Average unitary energy consumption associated with off-farm pumping and**
 271 **transportation (q_{pump}), and on-farm distribution and application(q_{plot}) stages for both surface**
 272 **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

273 The evolution of the CF also follows a downward trend (Figure 2c). Between 2005 and 2011, the CF
 274 decreased by 24.9%, (3,295 million kg (Mkg) of CO₂ equiv. in 2005 and 2,486 Mkg CO₂ equiv. in
 275 2011). These emissions represent 0.8% of the total GHG emissions inventory for Spain, as reported
 276 by the Spanish Ministry for Agriculture and Fishing, Food, and Environment under the United
 277 Nations Framework Convention on Climate Change (MAPAMA, 2017). The cutback of the CF is
 278 due to the decrease of both fractions: the CF_{sw} decreased by 27%, while the CF_{gw} decreased by
 279 21.6%.

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

283 From a water perspective, the largest share of the WF_{blueSW} in the two reference years was allocated
 284 to the cultivation of non-permanent crops, particularly cereals and industrial and fodder crops
 285 (Figure 3a). Over time, however, the WF_{blueSW} of non-permanent crops decreased overall by 48.2%
 286 (equivalent to an absolute reduction of -2,894 hm³). On the other hand, the WF_{blueSW} of permanent
 287 crops remained stable between 2005 and 2011, with a net reduction of 0.9% (equivalent to -35 hm³).

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.

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

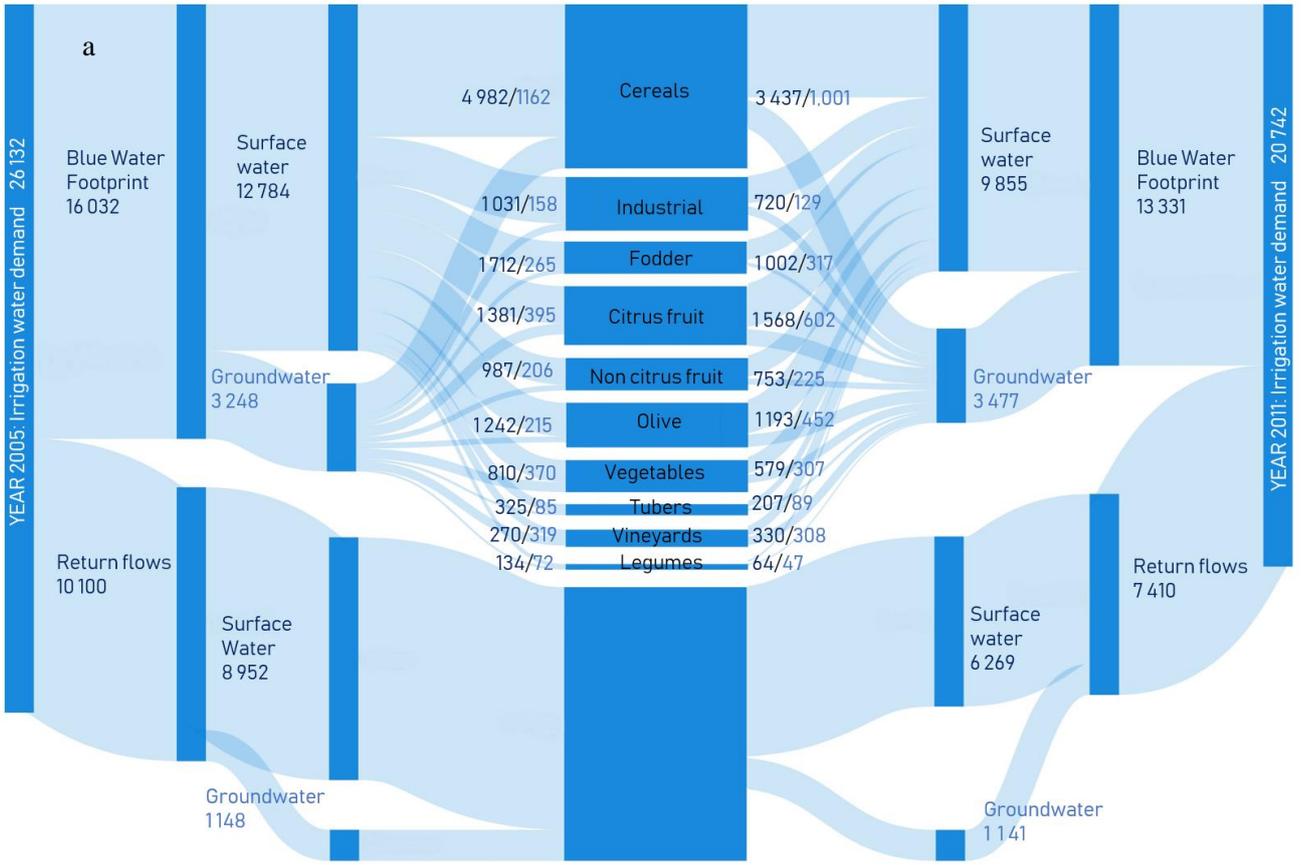
294 The largest fraction of return flows during the two reference years corresponds to RF_{SW} , and to a
295 lesser extent to RF_{GW} (Figure 3a). Over time, the RF_{GW} remained stable, while the RF_{SW} decreased by
296 30% between 2005 and 2011.

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

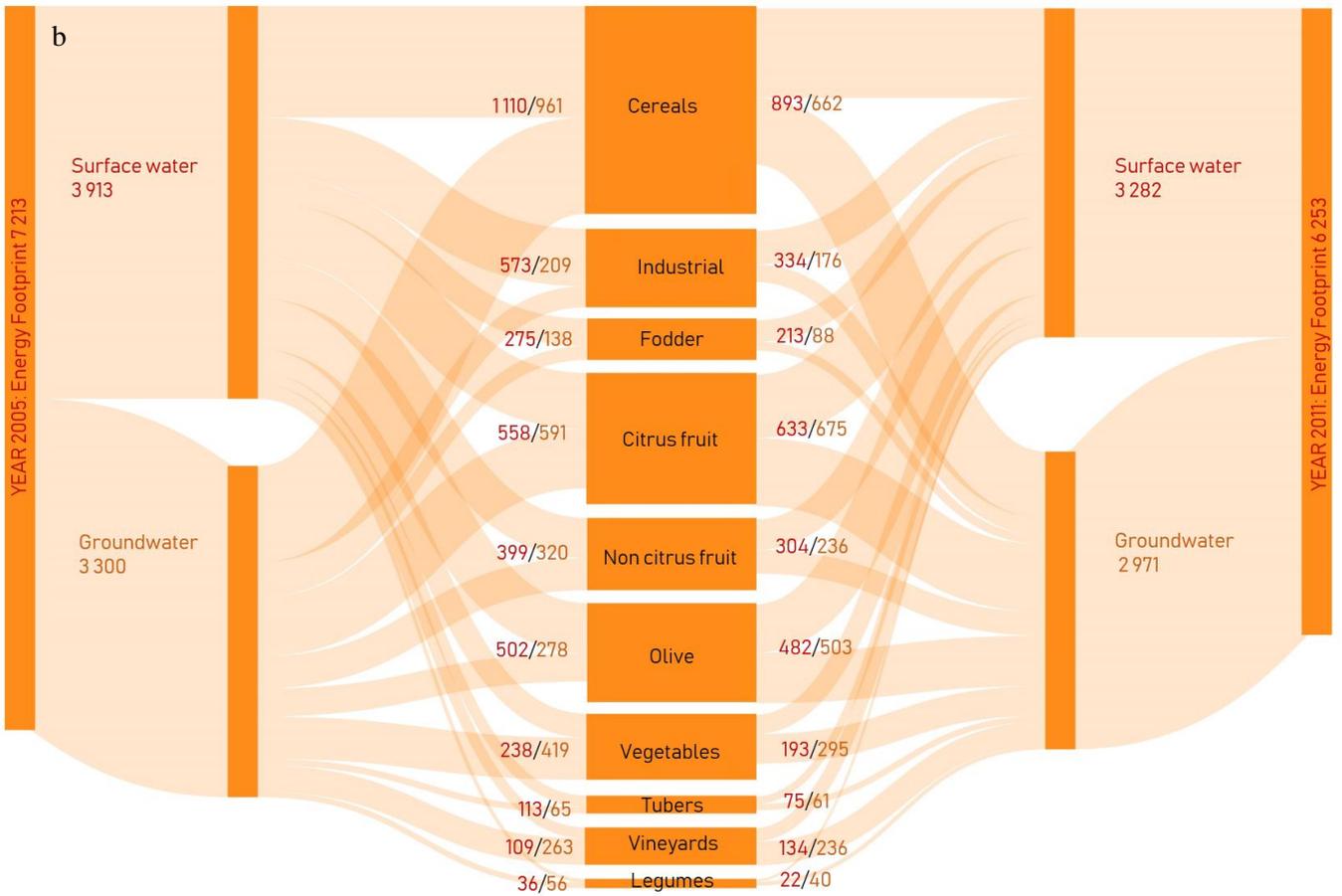
302 The growing cultivation and irrigation of woody permanent crops with groundwater led to a 12.0%
303 increase in its EF_{GW} (equivalent to $+197 \text{ GWh}$). This increase is mainly due to the rise in the EF_{GW}
304 of olive and citrus trees.

305 The CF follows a similar trend to that of the EF , although in the CF case a generalized decrease is
306 observed for all crops and sources of water (Figure 3c). The CF_{SW} and CF_{GW} of non-permanent crops
307 exhibits the largest changes, with a net reduction of 54.4% (equivalent to -395 million kg CO_2
308 equiv.), and 50.5% (equivalent to -306 million kg CO_2 equiv.). These sharp decreases are linked to
309 the reduction of the CF_{SW} of cereals and industrial crops and, similarly, to the decline of the CF_{GW} of
310 cereals and vegetables. With respect to the permanent crops, the CF_{SW} also decreased overall by
311 16.0% (equivalent to -99 million kg CO_2 equiv.), mainly as a result of non-citrus fruit and olive
312 trees. The CF_{GW} of permanent crops remained stable with a net negative change equivalent to $<1\%$.

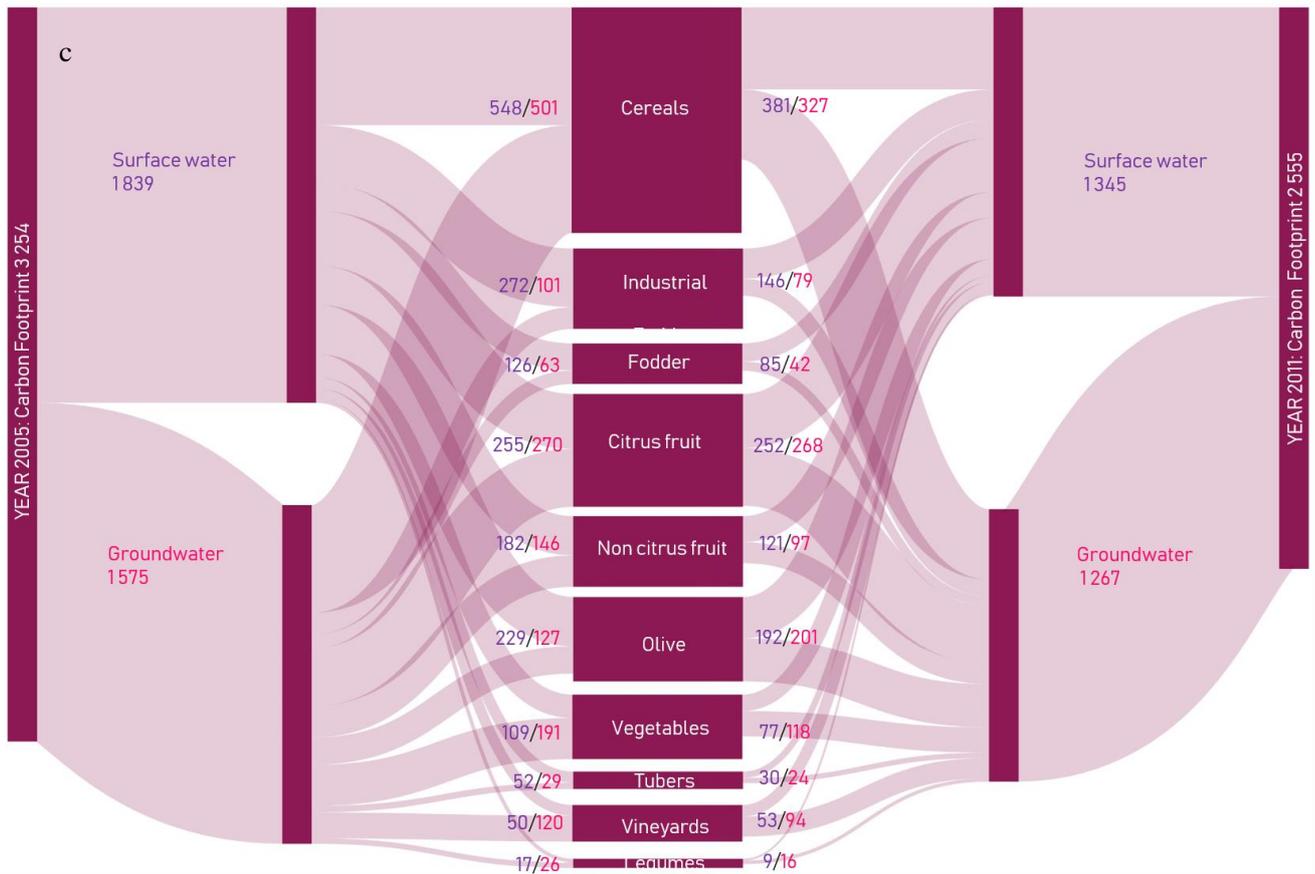
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317 **Figure 3. Surface and groundwater (a) blue water footprint (hm³), (b) energy footprint (GWh),**
 318 **and (c) carbon footprint (million kg CO₂ equiv.) of the main irrigated crops in Spain in 2005**
 319 **(left) and 2011 (right).**

320 Alongside with the net changes in water, energy and emissions reduction, in the relative efficiencies
 321 have also experienced remarkable changes (Table 4). From a water perspective, the efficiency of
 322 irrigated agriculture has improved by 7.6%. However, the increase in water use efficiency has made
 323 the irrigation systems more energy-dependent, increasing the relative energy costs by 9.2%. From an
 324 emissions perspective, the emission rate follows the evolution of the emission intensity of the
 325 electricity production mix. This intensity increases, initially driven by an increasing penetration of
 326 combined cycle natural gas (with very high associated CH₄ emissions); it starts to decrease
 327 afterwards due to the penetration of renewable energies. The observed increment in the last period is
 328 due to the domestic coal promotion policy initiated in 2010. Overall, there was a reduction of 11.7%
 329 between the beginning and the end of the period analyzed.

330

331 **Table 4. Efficiency rates in water, energy, and emissions of irrigated areas in Spain for the**
 332 **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

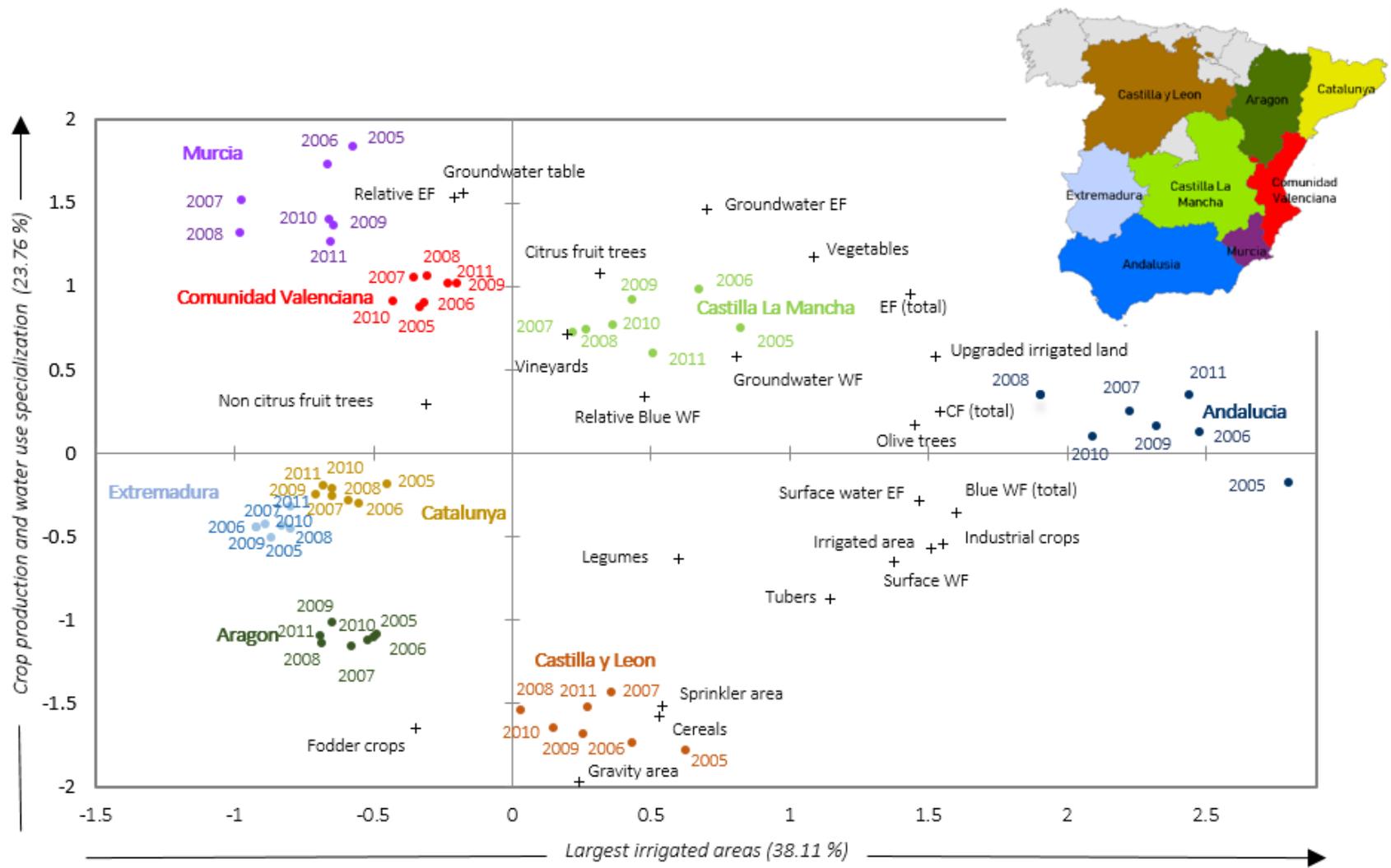
333

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

338 Overall, the larger WF, EF, and CF are linked to the administrative regions with large irrigated
 339 schemes, that have experiencing the largest upgrades of their irrigation systems, and are highly
 340 specialized in the production of permanent crops and the use of groundwater (Figure 4, top right
 341 quadrant). These areas overlap with the southern half of Spain (i.e., the Andalusia and Castilla-La
 342 Mancha regions). The central and northern parts of the country (the Castilla y Leon region) also have
 343 large irrigated areas, albeit mostly devoted to the cultivation of non-permanent and low value crops
 344 that rely heavily on the use of surface water (bottom right quadrant). In the eastern and southeastern
 345 parts of Spain (the Murcia and Comunidad Valenciana regions), the irrigated area is moderate, but it
 346 is also highly specialized in the production of permanent crops (mostly citrus trees) and high added-
 347 value vegetables, heavily reliant on the use of groundwater (top left quadrant). The relative energy
 348 costs here (kWh/m³) are among the highest in Spain. Other regions like Aragon, Extremadura, and
 349 Cataluña are less specialized, and the irrigated area is smaller in comparison with the neighboring
 350 administrative regions (bottom left quadrant). Lastly, it is important to highlight that the changes in
 351 irrigated areas and water demands observed between 2005 and 2011 have not altered the
 352 geographical specialization pattern across the country.

353

354



355

356 **Figure 4. Factorial analysis describing the typology of major irrigation regions (NUTS2) in Spain and its linkage to the water,**
 357 **energy, and carbon footprints.** Note: grey areas in the map represent regions with little irrigation development (overall representing
 358 <6% of the national irrigated area).

359 Discussion

360 The results of this study show that the water demand of irrigated agriculture in Spain (*Irr*) dropped by
361 21% between 2005 and 2011, which is equivalent to a net savings of 5,391 hm³. The factors contributing
362 to this reduction are diverse and cannot just be attributed to irrigation efficiency improvements. On the
363 one hand, the consumptive use of blue water (WF_{blue}) decreased by 2,700 hm³ mainly due to a reduction
364 in harvested production (-1.1% with respect to 2005 levels) but, most importantly, due to the more
365 favorable climate conditions and crop choices in 2011 (higher P_{eff} and lower CWR), which reduced the
366 relative blue water footprint of crops by 9% (4,830 m³/ha in 2005 and 4,380 m³/ha in 2011). This
367 confirms that, at the most, 50% of the achieved water savings (equivalent to 2,690 hm³) can potentially
368 be attributed to improvements in technical irrigation efficiency resulting from the replacement of the old
369 open air channel distribution infrastructure by pressurization pipe networks. Under this scenario, the
370 water savings resulting from improved efficiencies would have reached and actually surpassed the target
371 of 2,500 hm³/year set in the PNR-2008 (MAPA, 2001a), and the Shock Plan 2006–2008 (MARM,
372 2006).

373 Nevertheless, this hypothesis that it is efficiency improvements that have led to the met the targeted
374 water savings cannot be confirmed. In fact, if the (dry) climate conditions of the year 2005 had prevailed
375 in 2011, this would have led to a 9% decrease in the *Irr* (equivalent to net reduction of -2,344 hm³).
376 Under this scenario, net savings attributed to efficiency improvements would only have reached +1,800
377 hm³. These findings are in line with other studies (i.e., Birkenholtz, 2017; Lopez-Gunn et al., 2012;
378 Molle et al., 2017; Pfeiffer and Lin, 2014); and where it has been proved that water use efficiency
379 policies have failed to achieve ambitious water savings targets and, in the worst case, to lead to an
380 increase in water consumption.

381 Berbel et al. (2015) argued that water efficiency polices in areas suffering from over-allocation might
382 deliver real water savings as long as they are accompanied by a number of additional measures,
383 including: 1) a cap on the water extractions and on the further expansion of irrigated area; and 2) re-
384 assignment of the water savings to the environment to release pressure on the system. In this respect, the
385 results of our analysis show that between 2005 and 2011 the irrigated area remained fairly stable. Only a
386 slight increase of +0.3% was registered due to an expansion of irrigated areas in the Comunidad
387 Valenciana and Aragon regions, which was partly offset by the decrease experienced in some of the
388 largest irrigated regions (Castilla-La Mancha and Castilla y Leon) (see Figure 4). Although the

389 establishment of caps on water extractions cannot be tested, the results of our study show that the shift
390 in crop patterns has in fact had a positive impact by driving the progressive replacement of water-
391 intensive herbaceous crops (sugar beet, cotton, and maize) by high-value and less water-intense woody
392 crops (particularly olive trees, citrus trees, and vineyards). According to our results, the average water
393 demand per crop between 2005 and 2011 decreased by 14% (from 7,660 m³/ha to 6,610 m³/ha) and
394 would have remained at 6% (from 7,660 m³/ha to 7,220 m³/ha) under constant climate conditions. The
395 observed change in crop patterns confirms the results of Berbel et al. (2015) for southern Spain.
396 However, it differs from other studies (i.e., Birkenholtz 2017 or Rodriguez-Diaz et al. 2011, 2012), who
397 found that shifts in crop patterns actually led to more water-intensive production.

398 The shift toward high-value crops has also come at the expense of an increasing use of groundwater.
399 This can be largely explained by the fact that groundwater is more resilient to climate variability (Calow
400 et al., 2010) and that it is the preferred source of water for farmers in order to avoid risks and secure the
401 production of high-value crops. As Figure 4 shows, the highest use of groundwater for irrigation is
402 actually concentrated in the largest irrigated regions in Spain, namely, Andalusia, Castilla-La Mancha,
403 Comunidad Valenciana, and Murcia, which are also the largest producers of cash crops. Some of these
404 regions support the cultivation and export of berries and fresh vegetables, with apparent water
405 productivities of €8.5/m³ (Aldaya et al., 2010) and €7/m³ (Dumont et al., 2011), respectively. As pointed
406 out by De Stefano et al. (2014), groundwater in the period 2005–2008 generated at least 30% of the
407 economic value of the national agricultural production of Spain, and this share is likely to keep growing
408 because of the prevailing shift in crop patterns.

409 The upgrading of irrigated infrastructures has also had implications from an energy and emissions
410 perspective. The overall decrease in the *EF* (-13%) is mainly related to the favorable climate conditions
411 in 2011, which contributed to: 1) a decrease in the overall water demand (*Irr*); and 2) a reduction in the
412 groundwater table depth, and consequently groundwater pumping costs ($q_{\text{pump GW}}$), which represented at
413 least 75% of the energy bill during the analyzed period. Our estimates for $q_{\text{pump GW}}$ during the period
414 analyzed show a slight decrease (0.59 kWh/m³ in 2005 and 0.48 kWh/m³ in 2011), and are slightly
415 higher with the average value of 0.39 kWh/m³ estimated by Corominas (2010). This difference might be
416 attributed to the fact that the $q_{\text{pump GW}}$ calculation developed in this paper is sensitive to changes in the
417 water table depth, which helps gain a more accurate estimate of price changes between dry and wet
418 periods.

419 The literature on irrigation efficiency points to the fact that conversion into pressurized systems entails
420 higher energy costs, and this is often the main driving factor motivating farmers to ultimately save water
421 resources (Berbel et al., 2015; Rodriguez-Diaz et al., 2012; Soto-Garcia et al., 2013). Our study suggests
422 that despite the overall decrease in the EF , the average unitary costs (kWh/m^3) at the national level have
423 increased only moderately (Table 4). When looking separately at the unitary costs per irrigation system,
424 surface water-dependent systems (EF_{sw}) have seen cost increases of 4% ($0.21 \text{ kWh}/\text{m}^3$ to $0.22 \text{ kWh}/\text{m}^3$),
425 whereas in groundwater-dependent systems the EF_{GW} has actually decreased by 7% ($0.61 \text{ kWh}/\text{m}^3$ to
426 $0.57 \text{ kWh}/\text{m}^3$). Once again, if the dry 2005 climate conditions had remained constant over the study
427 period, the EF_{sw} and the EF_{GW} would have increased by 5% and 15%, respectively. While our results
428 confirm an upward trend in the energy intensity of irrigated systems, the observed increase is fairly
429 moderate compared with other assessments reporting energy costs increases above 70% (Jackson et al.,
430 2010; Berbel et al., 2015).

431 From an emissions perspective, the reduction in the CF is greater than the overall EF decrease, and the
432 dampening factor modulating this different behavior is the decreasing emission factor of electricity
433 production from $0.46 \text{ kg CO}_2 \text{ equiv.}/\text{kWh}$ in 2005 to $0.40 \text{ kg CO}_2 \text{ equiv.}/\text{kWh}$ in 2011 (Figure 2c). This
434 reduction is due to the mitigation policies implemented in the electricity sector with an increased
435 penetration of renewable energies (11% in 2005 and 31% in 2011) in the electricity production mix of
436 technologies in compliance with European Union targets (REE, 2006 and 2012).

437 The calculation of the CF relies on the assumption that electricity is the main source of energy for
438 irrigation. This assumption seems reasonable for the early 2000s, when at least 73% of the energy for
439 irrigation was provided by electricity and only 27% came from diesel pumps (Corominas, 2010).
440 Published work on CF s in Spain (e.g., Bartzas et al., 2015; Martin-Gorriz et al., 2017), and in other
441 countries such as India (Nelson et al., 2009; Shah, 2009) and China (Wang et al. 2012; Zou et al. 2015),
442 has shown the important impact of the energy source used for water pumping on the CF of irrigation.
443 Our results demonstrate that mitigation policies that reduce the CF of electricity generation have an
444 important effect on the sustainability of agricultural irrigation. GHG emissions from irrigation represent
445 only a small share of the emissions from agriculture. The size of this share depends on many factors
446 including type of irrigation, source of water, and type of crop. Literature estimates range from an 8%
447 share in northern areas of Spain in extensive cereal crops using surface water and modern irrigation
448 systems (Abraham et al., 2017), up to 35% in annual vegetable crops in the southeast of Spain using
449 more than 50% of water from external transfers and almost 40% of groundwater. According to the latest

450 energy and climate plans (PNIEC, 2019), the trend in the electricity sector is toward an 83% reduction
451 in the carbon footprint of electricity generation in 2030 compared to 2005 and almost complete
452 decarbonization in 2050. These future reductions in global warming emissions from electricity will
453 enhance the observed downward tendency in the *CF* of Spanish irrigation.

454

455 **Conclusions**

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

460

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

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477

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