RESEARCH

Trends in Water-Energy Nexus and Carbon Emissions Balance in Axarquia Region, Spain, in the Period 1990–2030

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Abstract

This research explores the dynamic interplay of water, energy, and carbon in Axarquia, Spain (1990–2030), focusing on the escalating water deficit and rising emissions. It seeks to comprehend the impact of subtropical crop expansion on regional resources. A comprehensive methodology integrates data on water demand, alternative sources and energy-intensive processes. Key methods include assessing the influence of subtropical crops on water requirements by calculating the FAO 56 crop coefficient (Kc), the total annual energy (GWh) as a consequence of the volume of water demanded, identifying the predominant water sources and quantifying CO_2 emissions by calculating the carbon footprint balance, providing a holistic view of regional resource dynamics. The methodology developed here can be adapted to basins elsewhere and can be a useful tool to help the design of water management policies in basins where the balance of the Water, Food, Energy nexus is of particular interest. The study reveals a substantial 30% surge in water demand due to exponential growth in subtropical crops. Additionally, energy-intensive processes linked to alternative water sources contribute to a projected surge in emissions (2022–2030), indicating significant regional challenges. Axarquia faces imminent challenges with a widening water deficit and escalating emissions. However, the region emerges as a vital carbon sink, evidenced by the net carbon balance. With 176,413 tCO_2eq sequestered by cultivated plant mass, the study underscores the potential for environmental improvement and climate change mitigation in the region.

Highlights

- The increase of subtropical crops in Axarquia (Spain) causes water constraints.
- Axarquia: 42 hm^3 water deficit, intensified by crop demands, avocados and mangoes.
- CO_2 in agriculture to rise by 2030 due to changing crops and energy methods.
- Water-energy confluence predicts alarming 80 GWh/year surge in agricultural usage.
- Axarquia sequesters 176,412 tCO_2 annually, supporting sustainability.

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1 Introduction

Global water use has increased nearly sixfold over the last 100 years in order to sustain growing food demand and rising standards of living (Wada et al. 2016). Increasing agricultural productivity faces constraints from the demands of climate change and the resulting impacts on key natural resources such as water and soil. Such challenges have the potential to attenuate yield expansion and precipitate a repositioning of agroclimatic zones towards the northern latitudes, thereby exerting influence on the prevailing patterns of crop cultivation (European Commission 2023).

Despite the uncertainty surrounding the impact of climate change, the frequency and intensity of droughts and the increase of global temperatures are evident (Liu et al. 2018). The most affected areas are the arid and semi-arid regions of the world (Bajany et al. 2021), where the available water resources are overstretched in the different sectors (urban, industrial, and agricultural). In these regions, the so-called "basin closure" has occurred (Expósito and Berbel 2019; Molle et al. 2010).

Palomo-Hierro et al. (2022) explain that in the pursuit of addressing water crises through climate change mitigation and adaptation, policymakers are confronted with two primary avenues: supply-side interventions, involving engineering instruments to augment water availability, and demand-side interventions, employing economic instruments to modulate consumption patterns in areas where basin closure has occurred. Therefore, water resources need to establish policies that balance their different uses when demand continues to grow, and it is impossible to increase supply.

In any case, we must consider the fact that other external factors such as unstable food prices, financial crisis, and political instability directly affect the management of water resources. In fact, investment in water saving and conservation technologies has been a common response to limited supply in closed basins, similar to the response of increased energy consumption (Zaman et al. 2012).

Therefore, another problem that needs to be addressed is moving and treating water, which are energy-intensive processes. Therefore, an accurate prediction of energy use is essential to establish an electricity supply and demand plan (Perelman and Fishbain 2022; Yi et al. 2022). The water-energy-food (WEF) nexus has recently emerged as a priority research in academic and institutional platform (Zhang et al. 2019).

A recent collaborative effort between researchers, policy makers and practitioners has produced the WEF Nexus Index, using the methodology developed by the European Commission JRC Competence Centre on Composite Indicators and Scoreboards. It serves as a valuable tool to quantify a country's performance in managing its WEF resources and to identify areas of strength and weakness in WEF resources (Simpson et al. 2022).

In the case of Spain, it is ranked 42nd out of 184 countries evaluated. Of the three pillars evaluated, Spain obtained its highest value for the Water pillar (71.2), followed by the Food pillar (68.4) and the Energy pillar (51.2). Nevertheless, it should be kept in mind that the index is fundamentally a cross-sectional snapshot in time and given the current critical conditions of climate variability (the El Niño–Southern Oscillation (ENSO) climate phenomenon) and ongoing climate change, the index could change in the short term. Indeed, this recently happened in Uruguay (Pieper 2023; Taylor 2023), a nation that in the 2022 ranking (WNI 2023) held 23rd position, above Spain; however, given the current unfortunate conditions, it would rank far below Spain.

WEF nexus involves several concepts (Huckleberry and Potts 2019):

a) water-energy, which refers to energy consumption for capturing, storing, transporting and treating water, as well as for wastewater treatment.
b) energy-water, which measures water use for thermoelectric or hydroelectric power production.
c) energy-food, which measures energy use for machinery and equipment for crop cultivation and energy for transporting intermediate and final products.
d) water-food, relating to the water needed to grow crops. In addition, a 5th component concerns the use of biomass for energy production.

As far as we know, there is a lack of studies that analyse the use of alternative water sources, highly energy demanding, together with the capacity to compensate this CO_2 emitted by the new crops introduced using the new water resources available. This study aims to help fill this gap by analysing the CO_2 equivalent (CO_2eq) emitted and the CO_2eq captured in a predominantly agricultural area, where this productive activity can only be maintained by alternative water sources.

This analysis model helps to assess the achievement of the goals proposed by the governments of the main developed countries. For instance, 55% net emissions reduction compared to 1990 in the European Green Deal, 0% net emissions by 2060 in China, or 52% by 2030 in the case of the USA. The methodology used responds to this need to quantify net CO_2eq emissions at the local level, to assess the achievement of these targets in areas of highly intensive agricultural activity, relying on water sources linked to a high level of CO_2eq emissions.

The case study selected is the Axarquia Region on the south-eastern coast of Spain. It has intense agricultural activity and can be considered as a representative of an arid/semi-arid Mediterranean environment that needs to adapt to water scarcity. This study attempts to characterise the territorial area of Axarquia in agrarian, economic and hydrological terms. The approach focuses on studying the recent trajectory of the exploitation of water resources, describing as objectively as possible the socio-hydrological system that defines it. To that end, we apply the analytical framework recommended by the European Environment Agency called DPSIR (drivers, pressures, state, impact, and response model of intervention), which facilitates the analysis of environmental management. Given the above information, the main contribution of this study is the analysis of the CO_2eq balance and its relationship with the WEF nexus, focusing on the regional level. Drawing on the study by Espinosa-Tasón et al. (2020), we calculate the energy consumed as a function of the water demand of agricultural activity (including the use of new water sources). This clearly CO_2eq emitting process is compared with the CO_2eq captured by the crops resulting from this activity. The methodological novelty of this study is that it incorporates the environmental component into the WEF nexus on an analytical level. This methodology provides a tool to help the water management bodies to make decisions in line with the guidelines issued by the governments on climate, energy, and sustainability of agricultural activity. This analysis can be replicable to any arid and semi-arid areas that share similar water deficit features with the case study selected. Especially those coastal areas, where the use of desalinated water may become the only feasible solution to continue with agricultural activity.

In light of the above information, the main contribution of this study is that the analysis focuses on the regional level rather than on larger areas, as can be typically found in literature. Axarquia is the main producer of avocado and mango in Europe, crops which in recent years have been suffering from drought conditions due to low rainfall and limited water reserves. Furthermore, our analysis includes the carbon dioxide equivalent (CO_2eq) balance to observe its relationship with WE nexus.

2 Methodology

The case study focuses on the agricultural region of Axarquia (36°50′00″N 4°10′00″W) in the district of Vélez-Málaga, Málaga, Southern Spain (Fig. 1). The district has 31 municipalities covering an overall area of 1023.51 km². Temperatures are mild, both in winter and summer, ranging from an annual average of 9 ºC in the highest areas of the Sierra de la Almijara to over 17 ºC in the area of Vélez-Málaga and Torre del Mar. Minimum annual rainfall is recorded in the western part of the region, with values of 400 mm, and the maximum (of approximately 800 mm) in the Sierra de la Almijara. Annual sunshine is around 2600 h (Fernández et al. 2010). The lowest relative humidity is recorded in July (61.06%) and the highest in December (77.65%) (Climate-Data.Org 2022).

The basic source of material for this research is official, gaps in data have been filled with estimates in case not directly recorded. Figure 2 shows both the different data sources and the methodology used in the estimation of the variables.
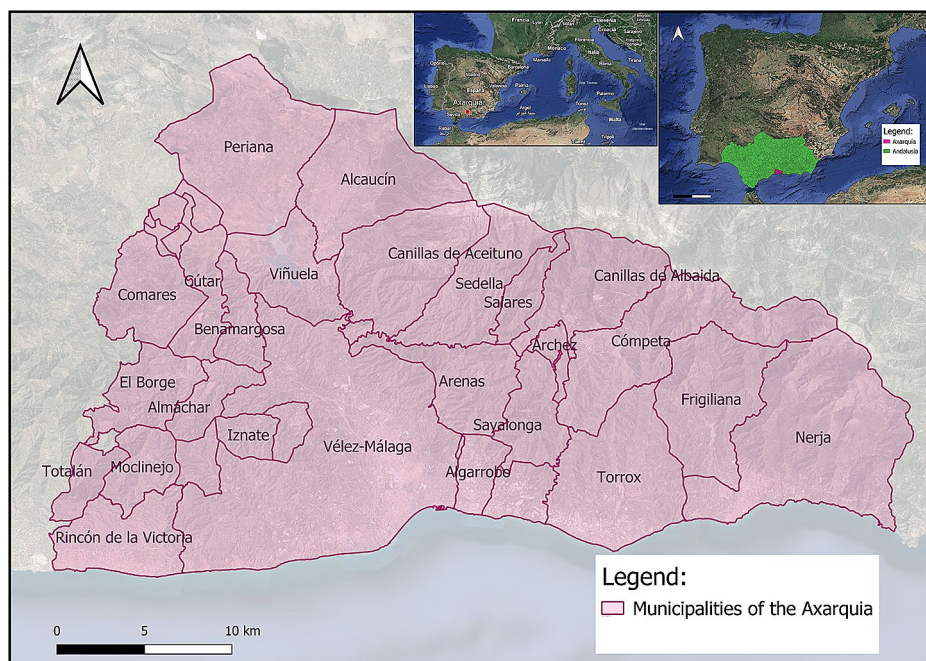

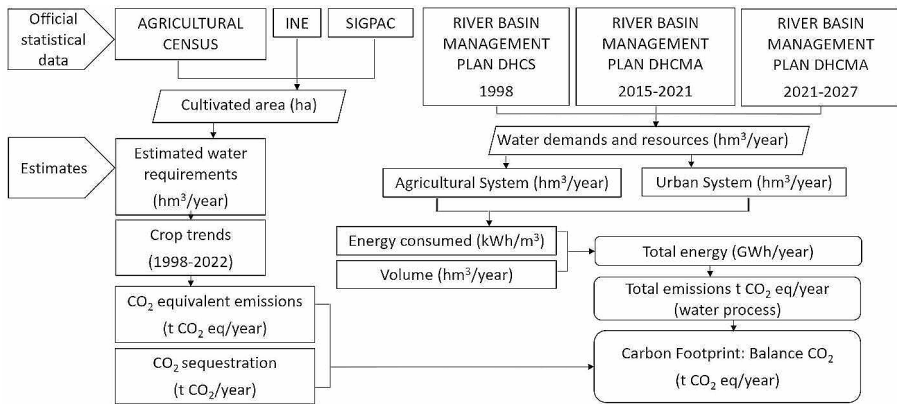**Fig. 1** Axarquia region in Malaga, autonomous community of Andalusia, Spain

Fig. 2 Methodology used

2.1 Driving Forces of Transformation: Demographic Changes and Unprofitable Traditional Agriculture

In the DPSIR analysis (Kristensen 2004), the first step is to identify the driving forces of the transformation of the region, which according to our analysis are population growth and lack of profitability in traditional agriculture.

The province of Malaga leads Spain in population growth for a second consecutive year (referring to 2021 and 2022), rising to over 1.7 million inhabitants. Axarquia has doubled its legal population in the last 20 years (INE 2023) due to the secondary homes and tourism activities. The five most populated municipalities in Axarquia are the coastal ones, bearing 84% of the regional population. The largest municipality in the region is Vélez-Málaga, home to 39% of the total population of the region.

The exceptional climatic conditions throughout the fertile lowlands and the coastal area make the cultivation of subtropical crops possible. The lack of profitability of traditional agriculture and the expectations of high yields of the new subtropical fruit species have been the two driving forces behind the transformation of the agricultural landscape in the region. There was an increase of 15,000 ha in the cultivated area during the period 1998–2022 (National Statistics Institute (INE) period 1998–2017; Geographical Information System for Agricultural Plots (SIGPAC) period 2018–2022), mainly due to the conversion of pasture and dry land into irrigated land. A large proportion of the new crops are citrus and subtropical ones, which have already displaced the traditional arable crops.

Subtropical crop plantations in the region have increased by 214% from 4.161 ha according to data from the Agricultural Census (1999) to 13,094 ha according to SIGPAC data (2022). Specifically, Vélez-Málaga has 66% of the province's subtropical crops. In spite of the increase in subtropical crops, other crops such as citrus and stone fruit trees have suffered 50% reduction extending from 548 ha (INE 2023) to 274 ha (SIGPAC 2022).

These changes have put pressure on water resources. As such, demand now exceeds the capacity of the system, with the total available water resources standing at 92.55 hm^3 according to the River Basin Management Plan (RBMP) for 2022–2027 (DHCMA 2022). The hydrological basins are small and, therefore, the available resources and water storage

capacity are limited; there is a proliferation of private storage reservoirs to alleviate this situation. In Axarquia there is only one large reservoir, located in La Viñuela, with a capacity of 165 hm³. The last few years drought conditions and increase in water needs in the region decreased the level of water in reservoirs to 9.7% of the available water (Fig. 3).

2.2 Crop Analysis

Data from the INE (2023) and SIGPAC (2022) have been used to conduct an analysis on the area cultivated in the region during the period 1999–2022. These data are divided to "Crop groups": Citrus and stone fruit trees, temperate fruit trees, subtropical fruit trees, nut trees, olive trees, vines, nurseries, other woody crops, vegetables and others. For further analysis, we have obtained data on unit crop areas for 2021 from the Regional Ministry of Agriculture, Livestock, Fisheries and Sustainable Development, specifically, data on woody crops: avocado, chestnut, lemon, mango, orange, loquat, olive, almond, vine and others (<100 ha); and arable crops: artichoke, pumpkin and courgette, green bean, lettuce, potato, cucumber, pepper, tomato, oats, barley, wheat, vetch and others (<100 ha).

2.3 Water Resources Analysis

The water analysis is based on the information extracted from the RBMPs for the Andalusian Mediterranean Basins (Table 1).

DHCMA data have been compared with the water needs of the cultivated area estimated in Sect. 2.1. For this purpose, the FAO-56 methodology used to estimate the irrigation needs of the different crops has also been followed, with the exception of fruit trees which have been taken from the studies by Moldero et al. (2021) and Moreno-Ortega et al. (2019). The net irrigation water needs have been estimated using the single crop coefficient method of the FAO 56 manual and applying a simple water balance, in which losses in the irrigation system and in distribution are already discounted (if the gross irrigation needs were calculated, losses would be taken into account). This coefficient is adapted to the phenology of the crops in the area and, as far as possible, local crop coefficients available in various studies are also used. The crop evapotranspiration ETc (mm) (Eq. 1), under the assumption that the crop does not suffer from water stress, is thus:
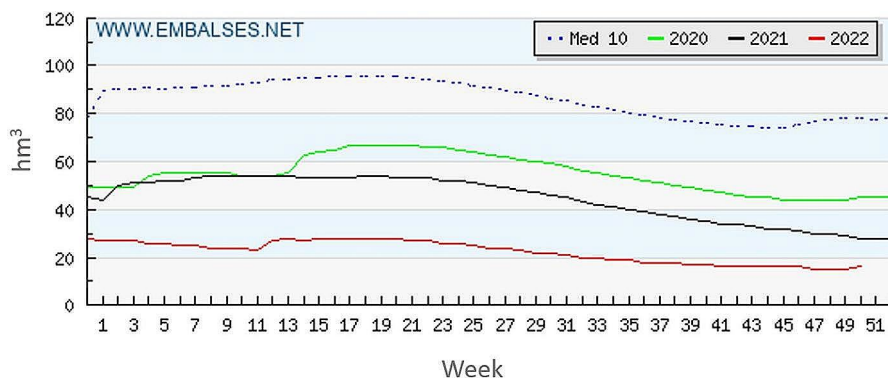

Fig. 3 Status of the La Viñuela reservoir over different years. Source: EMBALSES.NET (2022)

Table 1 Evolution of DHCMA water resources and demands

Resources (hm³)	Surface	Groundwater	Reused	Desalinated / Transfer	Total
1998	69	30	0	0	99
2015	47	32	0	0	79
2021	47	45	0	0	92
2030	46	33	11	15	105
Demand (hm³)	**Urban**[1]	**Irrigation**[2]	**Others**	**Total**	**Deficit**
1998	22	80	2	104	-5
2015	23	69	1	93	-14
2021	24	78	1	103	-11
2030	23	79	3	105	0

Source: Own elaboration based on data from the RBMPs (DHCMA, 2015, 2022; DHCS, 1998s). (1) The urban sector includes industrial demand; (2) Recognised concession rights

$$ETc = ETo \times Kc \tag{1}$$

where *ETo* is the reference evapotranspiration (mm) and *Kc* is the crop coefficient.

Both the calculation of irrigation needs and the data on resources and water rights (water demands) shown in Table 1 are based on an "average rainfall year" data.

2.4 Water-Energy Nexus (WE)

2.4.1 Agricultural System

At the same time as the use of non-conventional water sources has increased in the region, for the case of energy consumed by desalinated water, this has become more efficient in recent years due to emerging innovative technologies, such as the combination of reduced pre-treatment and efficient membrane technology, energy recovery systems and efficient brine management (AEDyR 2018; Melgarejo and Fernández-Aracil 2019). The energy consumed in desalinated and reclaimed water was obtained from Institute for the Diversification and Saving of Energy (IDEA 2010) and Lapuente (2012).

The total annual energy (GWh) consumed in the entire process of agricultural water supply in Axarquia has been calculated using the methodology proposed by Espinosa-Tasón et al. (2020). According to that study, the irrigation energy consumed depends on the volume pumped, the irrigation system, the efficiency of the pump and the fuel source of the engine (Eq. 2). The data for the variables and parameters is taken from the study itself, except for the pumped volume, where we use the water resources available in Axarquia presented in the 1998, 2015 and 2022 RBMPs.

$$Energy\,(kWh) = \frac{Volume\,(m^3) \times TH\,(m)}{367\;\mu_{pump} \times \mu_{motor}} \tag{2}$$

where TH is the sum of $Lift_{(m)} + H_{\min(m)} + f_{Losses(m)}$; $Lift_{(m)}$ is the depth to groundwater (m); $H_{\min(m)}$ is the typical working pressure of the different systems (for surface irrigation=0 bar, for sprinkler=3 bar and for drip=1 bar). Normally, additional pressure is added at the head of these systems to ensure uniformity, with pressure losses ($f_{Losses(m)}$) of about 20% assumed due to friction in the irrigation system; μ_{pump} is the efficiency of the pump at

converting the mechanical energy of a motor into hydrodynamic pressure and takes a value of 0.8 regardless of the power supply used; and μ_{motor} is the efficiency of the engine, which takes a value of 0.4 for diesel engines, where there is a large loss of energy in the form of heat, and 0.9 for electric motors, which are more efficient.

2.4.2 Urban Water Supply System

Energy consumed in the urban water supply has been estimated as the product of urban water demands, and the energy consumed per 1000 L of water (kWh/m^3). Urban demands used in the analysis are taken from the RBMPs (DHCMA 2015; DHCMA 2022; DHCS 1998). The energy consumption per m^3 of water has been obtained from (EUREAU 2021). According to EurEau, energy consumption for the abstraction, treatment and distribution of drinking water in Spain is $0.39 \; kWh/m^3$ and the energy consumption for the collection and treatment of wastewater is $0.55 \; kWh/m^3$ ($0.07 \; kWh/m^3$ collection and $0.48 \; kWh/m^3$ treatment). Total urban water supply: drinking water + wastewater = $0.94 \; kWh/m^3$.

2.4.3 CO_2 Emissions/Energy

To quantify CO_2eq emissions in our study area, we have used the annual average data for Andalusia. These data are based on the electricity mix, which indicates the energy sources used to produce electricity and CO_2 emissions associated with the generation of the electricity consumed. The electricity mix data are taken from Rodríguez et al. (2022), based on information obtained from the Comisión Nacional de los Mercados y la Competencia (CNMC).

After determining the emissions in tCO_2eq/GWh, we have used the energy data calculated for the agricultural sector and for the urban sector to compute the total CO_2eq emissions in Axarquia as the product of the two variables (tCO_2eq/GWh $\times$ GWh).

2.4.4 Carbon Footprint (CO_2 Balance)

We have calculated the carbon footprint as the difference between CO_2eq emissions (related to agricultural operations) and CO_2 sequestration (biogenic carbon) by crops. Throughout the study, we applied the following criterion for the sign of transfer: positive for carbon transfers from agricultural activity to the atmosphere and negative when transfers occur in the opposite direction, following the ISO 14,067 (2023) standard: *"ISO 14067 defines the principles, requirements and guidelines for the quantification of carbon footprint of products. The aim of ISO 14067 is to quantify GHG emissions associated with the life cycle stages of a product, beginning with resource extraction and raw material sourcing, and extending through the production, use and end-of-life stages of the product."* Therefore, CO_2 emissions have a positive sign, CO_2 sequestration has a negative sign, and the sign balance is the result of the net CO_2 emission.

To determine the CO_2eq emissions related to crop cultivation, we have used data from Martin-Gorriz et al. (2021) and Fernández-Lobato et al. (2021). These studies follow the methodology proposed by the ISO 14,064 (2023) standard, which, like the GHG Protocol (Smith et al. 2005), states that direct and indirect emissions must be considered when cal-

culating CO_2eq emissions. *"The Greenhouse Gas Protocol Initiative comprises two distinct but linked standards*:

- *- GHG Protocol Corporate Accounting and Reporting Standard: this document, provides thorough guidance for companies interested in quantifying and reporting their GHG emissions.*
- *- GHG Protocol Project Quantification Standard: is a guide for the quantification of GHG emission reductions. quantification of GHG emission reductions from specific projects."*

"ISO 14064-1 details principles and requirements for designing, developing, managing, and reporting organization-level GHG inventories. It includes requirements for determining GHG emission and removal boundaries, quantifying an organization's GHG emissions and removals, and identifying specific company actions or activities aimed at improving GHG management." Direct emissions refer to fuel consumption for field processing of the crop (tilling, sowing, pruning/shredding, thinning, mulching, phytosanitary treatments, basal dressing, and irrigation installation; emissions generated by fresh processing, harvesting and transport to storage; as well as NO_2 emissions from the soil due to fertilisation (IPCC, 2022). Indirect emissions are any emissions other than those mentioned above.

The values for the CO_2 capture of the different representative crops in the study area have mainly been taken from the research of Jumilla et al. (2010), who provided information for most of the crops in southeastern Spain (lemon, orange, vine, oat, barley, wheat, tomato, pepper, lettuce and artichoke). The capture values for avocado, mango, olive and almond trees were obtained from FAST (2023), NMB (2010), Mairech et al. (2020) and DGAFA (2013), respectively. In addition, the values of CO_2 emissions per unit area of each crop necessary to calculate the net CO_2eq balance have been obtained. The values have been taken from the Martin-Gorriz et al. (2021) research for each of the aforementioned crops, except for the olive tree, which has been obtained from Fernández-Lobato et al. (2021).

For some crops, information on CO_2 fixation has been determined from carbon concentration values using the molecular weight ratio proposed by Sofo et al. (2005) of 1.0 g carbon=3.66 g CO_2.

3 Results

First, we focused on the evolution of crops and water needs in the study area, followed by the water-energy nexus and carbon dioxide emissions, and finally we presented the results of the carbon footprint analysis.

3.1 Crop Trends and Water Requirements

The two crop groups that have registered the greatest increase in Axarquia in 1999–2022 are subtropical fruit trees, with an increase of 215%, and olive trees with an increase of 1097% (Table 2).

Table 3 shows the areas of each analysed crop in the agricultural region of Axarquia in 2021, as well as the distribution of the area that is irrigated for each crop. Subtropical

Table 2 Evolution of woody crops in Axarquia during 1999–2022

Crops*	1999[3]	2009[1]	2018[2]	2022[2]
Citrus and stone fruit trees	548	483	300	275
Temperate fruit trees	175	165	n/d	n/d
Subtropical	4161	5315	13,013	13,094
Nut trees	11	1307	1628	1658
Olive grove	1042	8827	12,496	12,475
Vines	81	1774	1663	1653
Nurseries	2	46	782	923
Other woody crops	2	59	819	829
Vegetables and others	n/d	572	1154	1034
Total, woody and horticultural crops	**6022**	**18,548**	**31,855**	**31,941**

Source: Own elaboration based on data obtained from the Census, INE and SIGPAC

(*) Area (ha) woody and horticultural Axarquia; (1) INE surface; (2) SIGPAC surface; (3) Agricultural Census surface

Table 3 Distribution of crops in Axarquia

Crops	Area (ha)	Percentage of irrigated crops (%)
Avocado	5227	100
Chestnut	225	100
Lemon	220	100
Mango	4092	100
Orange	128	100
Medlar	177	100
Olive	15,179	5
Almond	1779	0
Vine	2739	0
Others (< 100 ha)	346	100
Artichoke	200	100
Pumpkin and courgette	108	100
Green bean	245	100
Lettuce	154	100
Potato	344	100
Cucumber	119	100
Pepper	316	100
Tomato	725	100
Oats	201	0
Barley	201	0
Wheat	193	0
Vetch	163	0
Other (< 100 ha)	695	100
TOTAL	33,777	

Source: Own elaboration based on data from the Junta de Andalucía, update 2021 (Consejería de Agricultura Ganadería Pesca y Desarrollo Sostenible. Junta de Andalucía 2022)

fruit trees (avocado and mango) represent 66% of the total irrigated area (14,080 ha), and therefore play a fundamental role in the increase of water requirements. Irrigated olive trees occupy 5% of the total irrigated surface area in the region; therefore, despite the significant growth in this crop shown in Table 2, it is of far less importance in the water needs analysis conducted in this study.

The total estimated irrigation needs shown in Table 4 for 2022, according to FAO methodology, was 120 hm^3, while the allocated amount established in the RBMP (2022–2027) was 78 hm^3. The difference highlights the use of deficit irrigation for all crops, relative to the total water needs estimated by FAO 56 model. In contrast, RBMP assumes a smaller irrigated area than that estimated in this study, based on data from the Junta de Andalucía. Therefore, we considered a gap of 42 hm^3 between supply and demand of water resources in the region. However, allocated water rights as well as the irrigation needs are based on an annual average rainfall; in drought years, this water balance is negatively affected.

3.2 Water-Energy Nexus (WE)

Evolution of the energy consumed between 2005 and 2020 at provincial level shows an overall saving of 8 GWh, coming mainly from the transportation sector (Fig. 4).

3.2.1 Agricultural System

Table 5 shows the data used to apply the methodology of Espinosa-Tasón et al. (2020) in our estimation of the energy consumed in agricultural irrigation, as well as the results obtained for the 2030 for each type of water resource evaluated.

These results are shown in Fig. 5 highlighting the estimated exponential increase in energy consumption in the agricultural sector for the 2022–2030 horizon (80 GWh/year). The reduction in available resources due to ongoing droughts and the increase in demand from new crops necessitate the use of new water resources that are not immediately avail-

Table 4 Estimated irrigation requirements

	1999[3]	2009[2]	2018[1]	2022[1]	Increase (2022−1999)
Woody (ha)	6022	17,976	30,701	30,907	+24,885
Of which subtropical (ha)	4161	5315	13,013	13,094	+8933
Other (ha)	n/d	572	1154	1034	
Allocated water rights (hm^3)	73	76	78	78	
Irrigation requirements [4] (hm^3)	35	50	119	120	
RIS (Relative Irrigation Supply)	2.11	1.52	0.66	0.65	

Irrigation water requirements (IWR) 2022			
Crops	RBMP net IWR[5] (m^3/ha/year)	Estimated FAO 56 net IWR (m^3/ha/year)	Deficit Irrigation (m^3/ha/year)
Citrus and stone fruit trees	4900	5375	-475
Temperate fruit trees	4650	4697	-47
Subtropical	5300	7500	-2200
Nut trees	2300	8233	-5933
Olive grove	2700	4224	-1524
Vines			
Nurseries	4500	5610	-1110
Other woody crops	4000	4829	-829
Vegetables and others	5400	6259	-859

Source: Own elaboration. (1) Own estimate based on SIGPAC; (2) Own estimate based on INE; (3) Own estimate based on the Agricultural Census; (4) Estimate based on FAO methodology; (5) (DHCMA 2022)

Fig. 4 Final energy consumption by sector (Malaga). Source: Own elaboration based on data from the AAE (AAE 2022)
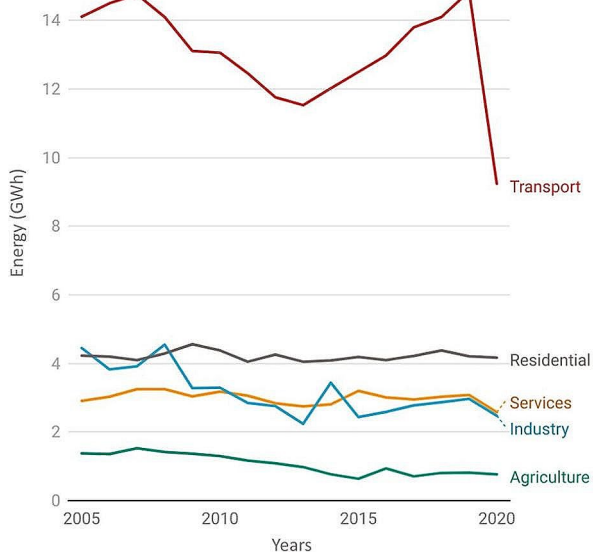

Table 5 Energy equation calculation data (estimates for 2030)

Horizon 2030	Surface Water	Groundwater	Reuse	De-sali-nation
Volume (Hm^3)	50	39	13	25
TH (m)	17	72		
Lift (m)	5	60		
Hmin (m)	10	10		
fLosses (m)	2	2		
μ motor	90%	90%		
μ pump	80%	80%		
Total energy (GWh)	**1.67**	**5.51**	**50.70**	**29.25**

Fig. 5 Energy used in agricultural water resources in Axarquia
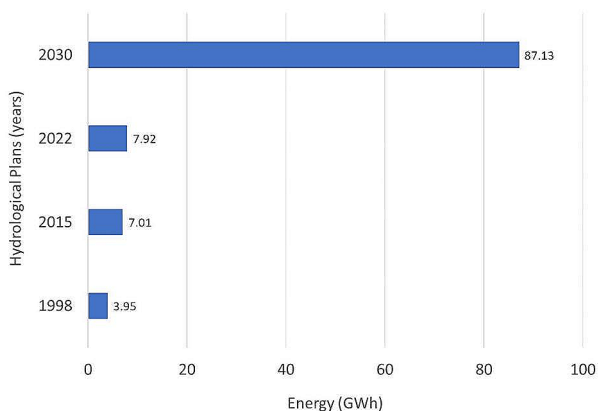
Table 6 National average water-energy nexus (Spain)

Supply	%	L/person/day*	m^3/ person/day	kWh/ person/day
Domestic	70	128	0.13	0.12
Industrial	16	29	0.03	0.03
Other	13	24	0.02	0.02

*Of the 237 L per inhabitant per day for water supply, 23% is unregistered water (55 L per inhabitant per day), leaving 182 L per inhabitant per day available for supply. Source: Own elaboration based on data obtained from AEAS and AGA

Fig. 6 Analysis of the urban water-energy nexus in Axarquia
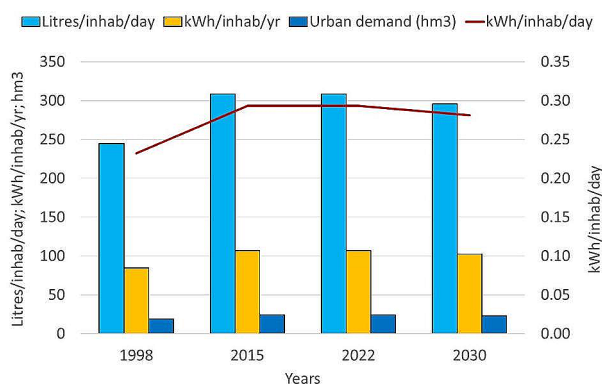
able but require the application of highly energy-intensive processes in order to be used, like desalination, wastewater reclamation and deep groundwater.

3.2.2 Urban Water Supply System

According to EUREAU (2021), the average residential drinking water consumption in Europe is 124 L/inhabitant/day, the average household size is 2.3 people and transmission losses are 25%.

At the national level, the AEAS-AGA (2020) estimates that the annual urban water supply is 3730 hm^3 and the volume of treated wastewater is 4450 hm^3. The energy associated with collection, supply and distribution in pumping is 447 GWh/year, and in treatment 2225 GWh/year. In Spain, the average energy consumption per 1000 L of water is 0.95 kWh/m^3. The total amount of water leaving the distribution tanks for consumption is 237 L/inhabitant/day. The volume of unregistered water which includes apparent and real water losses is 23%. Therefore, of the 182 L available for supply, 70% is allocated for domestic use, 16% for industrial use and 13% for other uses. These values may vary depending on the size of the population. Table 6 shows the results obtained for the water-energy nexus at the national level based on these data provided by the AEAS-AGA (2020).

Extrapolating data (Fig. 6), we observe no significant changes in the trend in urban energy consumption, with values remaining practically constant over time. Towards the 2030 horizon, we see a slight decrease in electricity consumption, as a consequence of the adjustment predicted by the RBMPs in water demand for urban use. In the analysis of water consumption per inhabitant per day in Axarquia (40% higher than the Spanish national

average), we must consider the distortion produced by urban water consumption by non-residents, as the region is one of Spain's preeminent tourist destinations.

3.3 Energy and CO₂ Emissions

According to the CNMC (2022), emission intensity of the Spanish electricity grid mix is 259 g CO_2eq kWh^{-1}. As a result of the higher proportion of renewables and due to the reduction in coal production, emissions of the Spanish electricity system decreased from around 80 MtCO_2eq in 2015 to approximately 50 MtCO_2eq in 2019 (REE 2021). The emission factor has gone from 290 tCO_2eq GWh^{-1} in 2015 to 136 tCO_2eq GWh^{-1} in 2021 pointing out a reduction of more than 50%.

More than 95% of the Andalusian electricity mix is based on renewable sources and natural gas, which means that CO_2 emissions per unit of generation are 68% lower than the value recorded in 2000. Figure 7 shows the evolution of CO_2 emissions due to electricity generation (Rodríguez et al. 2022) in Andalusia.

Below, we show the results at regional level in Axarquia. Emissions are expressed in tonnes CO_2eq per year for the two sectors analysed.

Energy consumption in the agricultural water supply system is calculated for the different years of the RBMPs as follows: 1998: 3.95 GWh; 2015: 7.01 GWh; 2022: 7.92 GWh; Horizon 2030: 87.13 GWh.

We have the information for Andalusia, specifically the emission intensity of the Andalusian electricity mix, for the annual series 2009 to 2020, which we multiply by the GWh consumed to obtain the CO_2 emissions generated at regional level. We can observe the evolution of these emissions in Fig. 8.

The results show a similar increase over time to that observed in Fig. 5. The reasons for this increase include the implementation of desalination plants and reused water.

Energy generation in the urban water supply system (drinking water + wastewater treatment) is calculated for the different years of the RBMPs as follows: 1998: 18.05 GWh; 2015: 22.80 GWh; 2022: 22.80 GWh; Horizon 2030: 21.85 GWh.

Taking the mix for Andalusia for the annual series 2009 to 2020 shown in Fig. 7, we multiply the tCO_2eq by the GWh consumed to calculate the CO_2 emissions generated at the regional level. We can observe the evolution of these emissions in Fig. 9.

Fig. 7 Evolution of the CO_2eq emissions generated by the electricity mix at regional level in Andalusia. (Source: Own elaboration based on data extracted from the Junta de Andalucía)
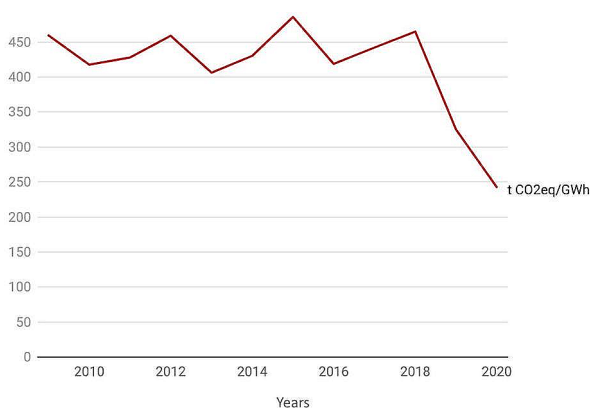
Fig. 8 Evolution of CO_2eq emissions due to electricity consumption in the agricultural system
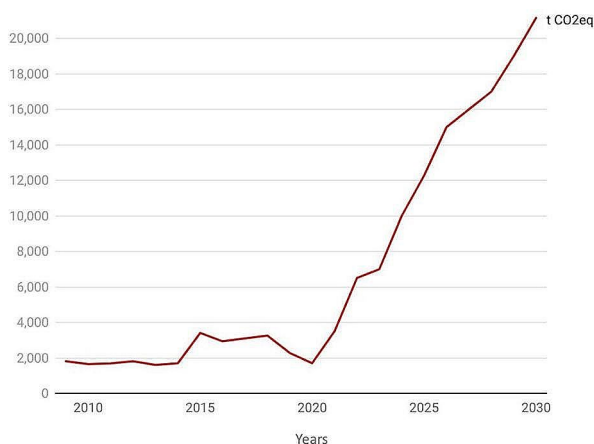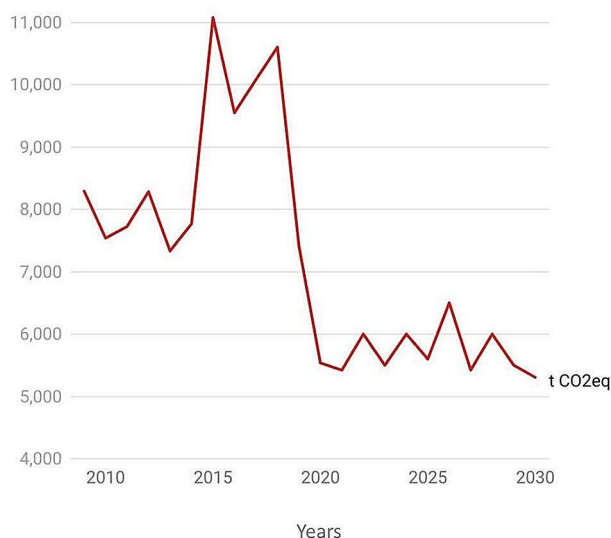

Fig. 9 Evolution of CO_2eq emissions due to electricity consumption in the urban water supply system

The results show that the emissions ranged from around 5000 tCO_2eq to 11,000 tCO_2eq. The fluctuations shown in Fig. 9 are due to energy production, which in turn, influences urban demand. The future outlook is positive as emissions from the urban electricity system decrease slightly.

3.4 Carbon Balance of Selected Crops

By calculating the net carbon balance of the agricultural area of Axarquia, we can quantify the environmental benefit of the agricultural crops in this region. Following ISO standards, to calculate this balance we sum the CO_2 capture or fixation of each crop (negative value) and the CO_2eq emissions of each crop (positive value). CO_2eq emissions, CO_2 capture and carbon balance for the selected crops and scenarios are presented in Table 7.

Table 7 CO_2 balance of crops in Axarquia

Crops	Area (ha)	Capture (t CO_2/ha/year)	Emissions** (t CO_2eq/ha/year)	Balance (t CO_2eq/ha/year)
Avocado	5227	-12.00	8.46	-3.54
Mango	4092	-9.00	8.46	-0.54
Lemon	220	-29.94	9.91	-20.03
Orange	128	-20.72	9.91	-10.81
Vine	2739	-19.00	8.46	-10.54
Olive	15,179	-6.00	1.16	-4.84
Almond	1779	-22.00	8.46	-13.54
Other woody crops	748	-17.00	8.46	-8.54
Oats*	201	-14.00	13.20	-0.80
Barley*	201	-13.00	13.20	0.20
Wheat*	193	-14.00	13.20	-0.80
Tomato	725	-31.79	14.90	-16.89
Pepper	316	-22.64	14.90	-7.74
Lettuce	154	-8.44	14.90	6.46
Artichoke	200	-12.97	14.90	1.93
Other grasses	1674	-17.00	14.90	-2.10
Total	33,776			
Total t CO_2eq /year		-374,440	198,028	-176,412

Source: Own elaboration. *Balance neutral, benefit is 0. CO_2 captured is equal to CO_2 emitted. **Greenhouse gas (GHG) emissions per crop (expressed as contribution per stage: fertilisers, pesticides, machinery, nursery, irrigation and field operations), expressed as CO_2 equivalent (CO_2eq)

Table 8 Overall summary of results in Axarquia

Variables analysed (Axarquia)	Year 2022
Total agricultural area (ha)	33,776
Estimated irrigation needs (hm^3)	120
Allocated water rights (hm^3)	78
Water deficit (hm^3)	42
Agricultural water-energy nexus (GWh)	7.92
Urban water-energy nexus (GWh)	22.8
Emissions (tCO_2eq/year) due to agricultural electricity consumption	1702
Emissions (tCO_2eq/year) due to urban electricity consumption	5536
Capture (tCO_2/year) by agricultural system	-374,440
Emissions (tCO_2eq/year) from complete agricultural system*	198,028
Emmision balance (tCO_2eq/ha/year)	-176,412

*Greenhouse gas (GHG) emissions per crop (expressed as input per stage: fertilisers, pesticides, machinery, nursery, irrigation and field operations), expressed as CO_2 equivalent (CO_2eq)

The results show a negative value of -176,412 CO_2eq per year, indicating a benefit to the environment. The negative balance shows that the 33,776 ha of crops in Axarquia are efficient sinks of atmospheric CO_2, highlighting the more positive environmental role of woody crops as opposed to herbaceous crops. Table 8 presents a summary of the results obtained in our analysis for each study variable.

4 Discussion

Three regions around the world, the Murray-Darling basin (MDB) in Australia, California in the United States, and Southern Spain in Europe have recently suffered prolonged droughts. All of them have similar water management challenges, socioeconomic characteristics, and dry and variable climates. For an effective and sustainable water resources management is crucial to share the measurement, processing, and communication of information on water availability and use (Escriva-Bou et al. 2020).

Based on the results of the analysis, we highlighted that the predominant crops in Axarquia are avocado and mango, accounting for 70% of the total irrigated area. This implies severe water limitations not only at the level of the Axarquia region but also at river basin level. The current water deficit in the study area is 42 hm^3. However, it could be much worse under extreme drought, as shown in the study by Tocados-Franco et al. (2023), where the extreme drought of the 2011–2012 hydrological period resulted in gross crop water needs of 6970 hm^3, with the deficit in the entire basin being 3613 hm^3.

A good water governance, understood as political, social, economic, and administrative systems that influence the use and management of water, is necessary (this includes who attains what water, when and how) (Berbel et al. 2023). The evolution of water needs and changes in crop patterns described in this article share similarities with the process outlined for California Central Valley by Mall and Herman (2019). However, a significant difference between these two regions lies in the greater importance of surface waters for DHCMA compared to the essential role of groundwater in the Californian case. The consequences for water supply risks mirror the process described for California, where the evolution in perennial crop areas, the development of water productivity, and the deterioration of supply risk are common features in both cases.

More recently, water managers facing with these serious water problems have invested heavily in improving water use efficiency and conservation (Al-Faraj et al. 2016; Schwabe et al. 2020). There are various ways to make more efficient use of water through modernisation of the irrigation systems. In the Andalusian Mediterranean Basins, the average efficiency of irrigation is 77%, while in the study area (Axarquia) the average efficiency is 85% (DHCMA 2022). Traditional systems centred on surface irrigation should be transformed in favour of more efficient systems, such as sprinkle and drip irrigation, which reach an efficiency of 80% and 90%, respectively. Drip irrigation technology is the best technology that provides a rational use of water resources, due to the saving of unproductive water that is lost by evaporation when using sprinkler technologies (Tsakmakis et al. 2018).

The overexploitation of water resources calls for the application of new methods and strategies that increase resource-use efficiency to benefit the farmer. Deficit irrigation techniques offer one of the most sustainable alternatives in a state of water deficit (Varzi and Grigg 2019). According to Endalu Tura and Tolossa (2020), in arid and semi-arid areas where water supply is scarce, deficit irrigation with different drought tolerant crops is preferable to full irrigation and more susceptible crops.

Among the many types of deficit irrigation techniques, deficit irrigation (DI) is based on the idea of reducing water inputs in the phenological periods in which a deficit does not appreciably affect the yield or quality of the crop, fully covering the plant's requirements in critical phases (Valcárcel et al. 2020). Since our results underline the particular importance of subtropical crops, we present a clear example of the benefits of this technique for this

type of crop. Under experimental conditions, application of DI to passion fruit (subtropical crop) was not found to affect either the yield or the nutritional values of the fruit, while making a more efficient use of the irrigation water supplied to the plant (Yzquierdo et al. 2020). Although applying modernisation techniques and new strategies focused on deficit irrigation offer some solutions to counteract the effect of water limitations, the reality is that most irrigated crop areas have already been largely modernised, with efficient drip irrigation systems in place.

A paradigm shift is now underway and there is a persistent increase in the adoption of wastewater and water desalination as a supply solution to meet ever-expanding water demand (Fagundes and Marques 2023). Deliberate wastewater reuse is typically characterised by the direct use of treated wastewater that adheres to specified quality standards. This atypical water source is often referred to as "reclaimed" or "recycled" water (McClaran et al. 2020). Moreover, seawater is an unlimited source of water for desalination processes, and an estimated 16,000 desalination plants are currently operational in 177 countries, with a total desalination capacity of about 95.35 million m^3/day (34,810 million m^3/year) (Bundschuh et al. 2021).

It is important to emphasise that, since the modernisation of Spanish irrigation at the beginning of the 21st century, there has been a change in trend with a reduction in water abstractions for irrigation, an increase in the use of non-conventional sources (desalination, reclaimed water) and an acceleration of technological progress in water saving and conservation (Berbel and Espinosa-Tasón 2020). In Spain, water conservation systems for irrigation (drip irrigation, sprinkling, scheduling and automation) have been shown to increase energy consumption for irrigation since 2005, and mature water economies such as Spain may exhibit both reduced water withdrawals and higher energy consumption (Espinosa-Tasón et al. 2020). The use of reclaimed water and water desalination are the solution currently being adopted in our case study area. This strategy seems to be against CO_2 emission reduction policies. The objective of this study is not to look for crops to replace the current ones, but to demonstrate that the net balance of CO_2eq emissions can be positive, even with these new water sources.

On the other hand, there are other alternatives developed around the world based on demand-side policies, such as economic instruments (water markets, water banks, water pricing) for improving water management in economic and social terms (Martínez-Dalmau et al. 2023; Montilla-López et al. 2016; Wheeler et al. 2014). It should be noted that water markets have been developed in Spain in the Andalusian Mediterranean basin, where our case study is located (Palomo-Hierro et al. 2015). However, water banks designed to reallocate water resources between irrigators only have been simulated by Gutiérrez-Martín et al. (2020) in the Guadalquivir River Basin (close to the case study), considering the environmental water demands of society and different scenarios of water scarcity within the agricultural sector. In Australia, sophisticated instruments such as forward contracting and extended leases are now included (Palomo-Hierro et al. 2022). In summary, these tools should be just understood as complementary economic instruments to be combined with other demand-side policy instruments.

Within the context of the WE nexus, we aimed to make a novel contribution by incorporating an environmental element. We therefore calculated the net carbon balance of the agricultural area in Axarquia, revealing a carbon sink ecosystem. Our results show that the more than 33,000 ha of cultivated agricultural area capture 176,412 tCO_2eq /year, which is a

substantial amount compared with the national average of more than 2 million tCO_2eq/year (Aguilera et al. 2020). If we focus on subtropical crops, it can be observed that the estimated CO_2eq emissions are higher than those shown in other countries. Specifically, a study conducted in Turkey reported GHG emissions from avocado production of 6.14 tCO_2eq/ha/year (Gökduman et al. 2022), while Astier et al. (2014), focusing on Mexico, calculated the total GHG emissions from avocado production at 1.86 tCO_2eq/ha/year, whereas our results show emissions from subtropical crops of 8.46 tCO_2eq/ha/year. We must continue to expand our knowledge on the water-energy-food-environment (WEFE) nexus. Many studies do not consider food and environmental variables, nor are the biophysical and socioeconomic aspects of these variables considered. Correa-Cano et al. (2022) develop a novel WEFE modelling toolkit that integrates the two aspects by combining different modelling approaches, including irrigation simulation, economic modelling and life cycle environmental assessment. These kinds of models are necessary to achieve improved forecasting relative to studies such as ours, such as the case of Valdez et al. (2016) in Mexico city, where a simulation model focused on the water, energy and greenhouse gas emissions nexus through rainwater harvesting predicted reductions in overexploitation of aquifers and CO_2 emissions.

Empirical studies focusing on different parts of Spain show that the increase in woody crop area in recent years has led to a greater accumulation of carbon in the form of living biomass, particularly in agricultural areas that had previously been cultivated with crops but were subsequently abandoned (Almagro et al. 2013; Martín et al. 2019). Similarly, in other Mediterranean systems (Novara et al. 2017), CO_2eq emissions and sequestration are strongly influenced by soil management, since the key in agricultural systems lies in the sequestration of carbon in the soil in addition to that of the crop itself (Aguilera et al. 2015a, b). It is also important to mention that benefits will be directly conditioned by the type of system the farmer has in place. Different studies show a wide variability in emission patterns, for both organic and conventional systems, which points to a high potential for improving GHG mitigation in both types of systems (Gutiérrez et al. 2017).

Accordingly, transforming the soil into a carbon sink could be a key element in mitigating GHG in Spain and counteracting the negative effects of the current water deficit. There is a need for scientific models that focus on innovation in techniques and strategies to make the system more sustainable. However, most studies are based on case studies at national scale, whereas the models should be applied at a more local scale. As such, our study provides more detail on the current situation at the regional level.

5 Conclusions

This study aims to improve the understanding of recent trends in the cultivation of subtropical crops in the agricultural region of Axarquia, considering the WE nexus, and incorporating an environmental component through the carbon footprint. Measures to reduce the water deficit can be found on both the supply and the demand side. Techniques such as improved irrigation efficiency, alternative cropping systems, or deficit irrigation are used to reduce irrigation demand. Alternative water sources such as desalinated water, treated wastewater or deep aquifers are the most commonly used options for increasing water supply. However, these alternative water sources are only possible through the application of energy-intensive

processes, meaning they are CO_2eq emitters. Forecasts indicate a worrying picture for the 2030 horizon, with an exponential increase in emissions in the period 2022–2030.

Analyses of the WEFE nexus consider interactions among water, energy, food and the environment. Our results show that the capture of CO_2eq by crops in agricultural areas may balance out the emissions caused by alternative water sources. This is the case in our case study, and we suggest that this analytical model should be incorporated as a management and feasibility analysis tool by the management bodies responsible for water management.

We have only considered net carbon emissions, but it would be worth extending this analysis to other environmental elements such as soil protection, water pollution, atmospheric emissions of pollutants, biodiversity, and landscape. In this sense, our examination of environmental impact reveals a positive balance: the $-176,413$ t of CO_2eq captured by the cultivated plant mass compensate for the emissions produced in the agricultural system, thus contributing to the improvement of the environment and the mitigation of climate change. The WEF nexus index (Simpson et al. 2022) for Axarquia could not be calculated because the data required are not available at a local level. Future research should incorporate more detailed analysis of this nexus for a better understanding of the net CO_2eq balance.

We consider it important to demonstrate that it is possible to produce food in a sustainable way, even in water-scarce regions. This requires finding solutions to reduce water and energy consumption, as well as the other environmental impacts of agriculture. In this sense, optimising water and energy use requires using new water sources efficiently to reduce energy consumption. It is also important to use efficient irrigation systems that save water, and to develop more drought-resistant crops, which require less water, and adopting good agricultural practices to help conserve soil and water.

On the other hand, scarcity, and specifically droughts, in arid and semi-arid areas have immense international importance on multiple levels, encompassing environmental, economic, social, and political concerns. Droughts in arid and semi-arid areas are not merely local problems but issues with profound international significance. The environmental, economic, social, and political consequences of these events necessitate international cooperation, resource sharing, and proactive measures to build resilience and address the underlying causes of water scarcity. Only through coordinated global efforts can we mitigate the impact of droughts on vulnerable communities and ensure a sustainable future for all.

Author Contributions All authors contributed to the study conception and design. Enrique Tocados-Franco: Investigation, Methodology, Conceptualization, Writing – original draft, Writing – review & editing. Javier Martínez-Dalmau: Conceptualization, Supervision, Writing – review. Jaime Espinosa-Tasón: Investigation, Conceptualization, Writing – review & editing. Nazaret M. Montilla-López: Supervision, Writing – review.

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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