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Influence of the Water Source on the Carbon Footprint of Irrigated Agriculture: A Regional Study in South-Eastern Spain

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Abstract: Curbing greenhouse gas (GHG) emissions to combat climate change is a major global challenge. Although irrigated agriculture consumes considerable energy that generates GHG emissions, the biomass produced also represents an important CO_2 sink, which can counterbalance the emissions. The source of the water supply considerably influences the irrigation energy consumption and, consequently, the resulting carbon footprint. This study evaluates the potential impact on the carbon footprint of partially and fully replacing the conventional supply from Tagus–Segura water transfer (TSWT) with desalinated seawater (DSW) in the irrigation districts of the Segura River basin (south-eastern Spain). The results provide evidence that the crop GHG emissions depend largely on the water source and, consequently, its carbon footprint. In this sense, in the hypothetical scenario of the TSWT being completely replaced with DSW, GHG emissions may increase by up to 50% and the carbon balance could be reduced by 41%. However, even in this unfavourable situation, irrigated agriculture in the study area could still act as a CO_2 sink with a negative total and specific carbon balance of −707,276 t CO_2/year and −8.10 t CO_2/ha-year, respectively. This study provides significant policy implications for understanding the water–energy–food nexus in water-scarce regions.

Keywords: agricultural irrigation; climate change; GHG emissions; carbon removal; water transfer; desalination; water–energy nexus

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1. Introduction

Anthropogenic greenhouse gas (GHG) emissions are the key driver of climate change [1]. Population growth, economic prosperity and evolving dietary demands are increasing the demand for food. The way we produce and consume (intensive farming systems, water and soil depletion, high levels of greenhouse gas emissions, etc.) needs profound changes to maintain productivity whilst promoting sustainability and resilience of the agro-systems [2]. In the context of promoting crop productivity and sustainability, irrigated agriculture may be one of the main suitable options against climate change [3–5]. An increase in irrigation demand, with the corresponding impact on energy consumption and GHG emissions, will lead to potential conflicts in terms of mitigation and adaptation policies [6,7].

Agricultural sustainability must be monitored based on adequate indicators. The Spanish Ministry of Agriculture, in its *Annual Report of Indicators* [8], considers GHG emission as an adequate indicator to provide an integrative vision of the agricultural sector sustainability. From the perspective of climate change and its mitigation, agriculture can contribute to both climate change and its mitigation. In the agricultural sector, GHG emissions come from the applied production techniques as well as from provided inputs (i.e., fertilisers, agrochemicals, irrigation water supply, energy supply). However, agriculture represents a carbon sink, capturing atmospheric CO_2 into the plant mass and the soil. Consequently, an analysis of the carbon footprint in agriculture needs to determine the carbon balance between GHG emission and CO_2 removal. A negative balance implies that the activity captures more CO_2 than it emits and therefore can be considered sustainable from a climate perspective. However, a positive balance implies the need to seek mitigation strategies such as innovative production techniques and alternative inputs to achieve sustainability.

Life Cycle Assessment (LCA) is a reference method to quantitatively evaluate the environmental impact across the entire supply chain in terms of energy-use efficiency, environmental effects and sustainability, including GHG emissions as a relevant indicator of global warming potential. For agri-food systems, LCA is increasingly being used to evaluate and analyse environmental and food security issues [9,10], including crop production [11,12], contributing to the creation of scientific knowledge for evidence-based policy-making [13].

Irrigated agriculture constitutes the largest consumer of freshwater in the water-scarce Mediterranean region and provides a major source of income and employment for rural livelihoods [14]. However, increasing droughts and water scarcity are jeopardising the availability and reliability of water resources for irrigation [15]. This is a limiting factor for economic development and has highlighted concerns regarding the environmental sustainability of agriculture in the region [16]. In this context, inter-basin water transfers are instruments of water planning that can play an important role in mitigating water scarcity and the effects of climate change [17].

Our study focuses on irrigated lands associated with the Tagus–Segura water transfer (TSWT); a 292-km-long canal that has transferred flows since 1979 from the Tagus headwaters river basin in central Spain, to the Segura River basin (SRB) in south-eastern (SE) Spain [18,19]. The SRB, despite being hot and dry, has witnessed remarkable agricultural development over the last decades, becoming one of the world's leading producers of fruits and vegetables [20]. An important part of this highly profitable business relies almost exclusively on the TSWT. Pellicer-Martínez and Martínez Paz [21] studied the possible effects that the latest climate change scenarios may have on the TSWT and predicted important reductions in snowfalls and snow covers, the recharge of aquifers and, consequently, the available water resources in the headwaters of the Tagus River basin. Moreover, the importance of water ecosystem services in the Tagus River basin has progressively been highlighted in recent years. The latter involves increasing demands to satisfy and safeguard multiple needs of consumers, the economy and the environment. Consequently, the decrease in water available for the transfer has led to bitter regional disputes [22]. Past and present perspectives on the SRB water shortage are well documented [19,23].

This chronic and problematic situation has driven the orientation of Spanish water policy since the beginning of the 21st century towards the widespread adoption of non-conventional water resources. Particular emphasis has been given to desalination as an alternative to other water supply options such as river regulation or new inter-basin water transfers [24]. As a result, massive seawater desalinisation has been implemented in the last decade as an alternative way to increase urban and agricultural supplies in SE Spain [23]. Seawater desalination effectively removes the climatological and hydrological constraints associated with continental water resources [25]. In addition, it circumvents the social and inter-regional conflicts associated with river regulation through dam building and long-distance inter-basin water transfers [26]. In such a way, desalination is alleviating the decrease in the water supplied by the TSWT in recent years. The downside is that the specific energy consumption for desalinated seawater (DSW) supply in the SRB (4.32 kWh m^{-3} [27]) is much higher than that of the TSWT (1.21 kWh m^{-3} [28]). This increases the GHG emissions of irrigated agriculture and jeopardises the effectiveness of climate change control policies.

Given the importance of irrigated agriculture in SE Spain, this study provides robust and objective estimates on GHG emissions under different scenarios, in which the TSWT supply is partially and fully replaced with DSW. Furthermore, in order to highlight the potential role of regional agriculture as a carbon sink, the CO_2 removals associated with the irrigation lands were estimated. Finally, potential ways to improve the sustainability of the agricultural use of DSW are proposed.

2. Materials and Methods

The analysis of the carbon footprint for the study area was developed in two phases: (1) the determination of the GHG emissions and CO_2 removals for the most representative crops in the study area; and (2) their extrapolation to the irrigation districts supplied by the TSWT to obtain global figures of the carbon balance.

Agricultural production data was used to estimate the carbon footprint for the most representative fruit and vegetable crops in the study area. In order to estimate the GHG emissions, LCA methodology has been applied, following the protocols standardised by the International Standards Organization in the ISO 14040 [29] and ISO 14044 [30] standards. Crop CO_2 removal rates were obtained from the results of experimental trials in the region published by other authors, as detailed in Section 2.4.

Several studies have found that irrigation water conveyance and application emit large amounts of GHGs [31–33]. Therefore, the carbon footprint was calculated under three water supply scenarios, in which there was a progressive replacement of the water supply from the TSWT with DSW. This is the main strategy included in the Spanish water planning to redress the persistent water deficit affecting irrigation in the SRB. Therefore, the sensitivity of the results for this variable is of special interest to analyse the carbon footprint implications of the planned agricultural water supply. Finally, we compare our results with other related studies.

2.1. Segura River Basin (SRB) and Tagus–Segura Water Transfer (TSWT)

The SRB is a highly productive agricultural region in SE Spain, whose economy is built primarily on the export of high-value vegetables and fruits. Its semiarid climate is characterised by hot, dry summers and sporadic intense rains in autumn. The mild-temperature winters allow vegetables to be grown in the open field. This area, with high-return agriculture, is usually referred to as 'the orchard of Europe' [34], since exports of horticultural products to EU countries may exceed 70% of the total production. It plays a major role in the basin's economy in terms of production and employment.

The SRB is one of the most water-stressed regions in the Mediterranean basin. The official estimation [35] is that the SRB water resources amount to 1602 Mm^3/year, which includes water transferred from central Spain through the inter-basin TSWT (322 Mm^3/year) and DSW (158 Mm^3/year produced in several desalination plants [27]). These resources fail to satisfy a total water demand of 1834 Mm^3/year, which includes 1546 Mm^3/year for irrigated agriculture (84% of the total). The mean annual water deficit amounts to about 400 Mm^3 [35], threatening the strategic agricultural production and bolstering conflicts between aggravated users [22]. The water shortage and conflicts explain the massive seawater desalination strategy implemented in the SRB by the Spanish government to guarantee the urban supply as well as foster irrigated agriculture [23].

The TSWT is one of the largest (292 km) inter-basin infrastructures in southern Europe. The rationale for developing that water transfer was that cities and tourism on the Mediterranean coast needed water to grow and that irrigated agriculture in the mild regions of SE Spain could achieve higher water productivity than in the inner regions. The TSWT is managed by its own operational rules, which give priority to the water uses in the Tagus River basin and depend on the volume stored in the Tagus headwaters reservoirs. As indicated in the official estimation of the SRB resources [35], currently and on average, barely 60% of the approved flows can be transferred. Such a decrease in the annual transferred flow is a situation that is predicted to intensify in the future as the pressure of climate change mounts in the Tagus River basin [21,36].

The increasing water shortage mainly affects irrigated agriculture, which currently amounts to 262,393 ha in the SRB, and has led to a serious problem of overexploitation in many aquifers [37]. The supply to farmers is organised by irrigation districts, which can be differentiated into two types: those using the water resources generated in the SRB, named 'traditional irrigation districts'; and, conversely, those that are mainly supplied by the TSWT, named 'Tagus–Segura irrigation districts'. Our study targets the latter, which represents a net irrigated area of 98,923.6 ha organised into 18 Agricultural Demand Units (ADUs), as shown in Figure 1. They are particularly important in the SRB economy, in terms of both production value and employment (2000 M EUR/year and 58,500 annual work units, respectively [35]).

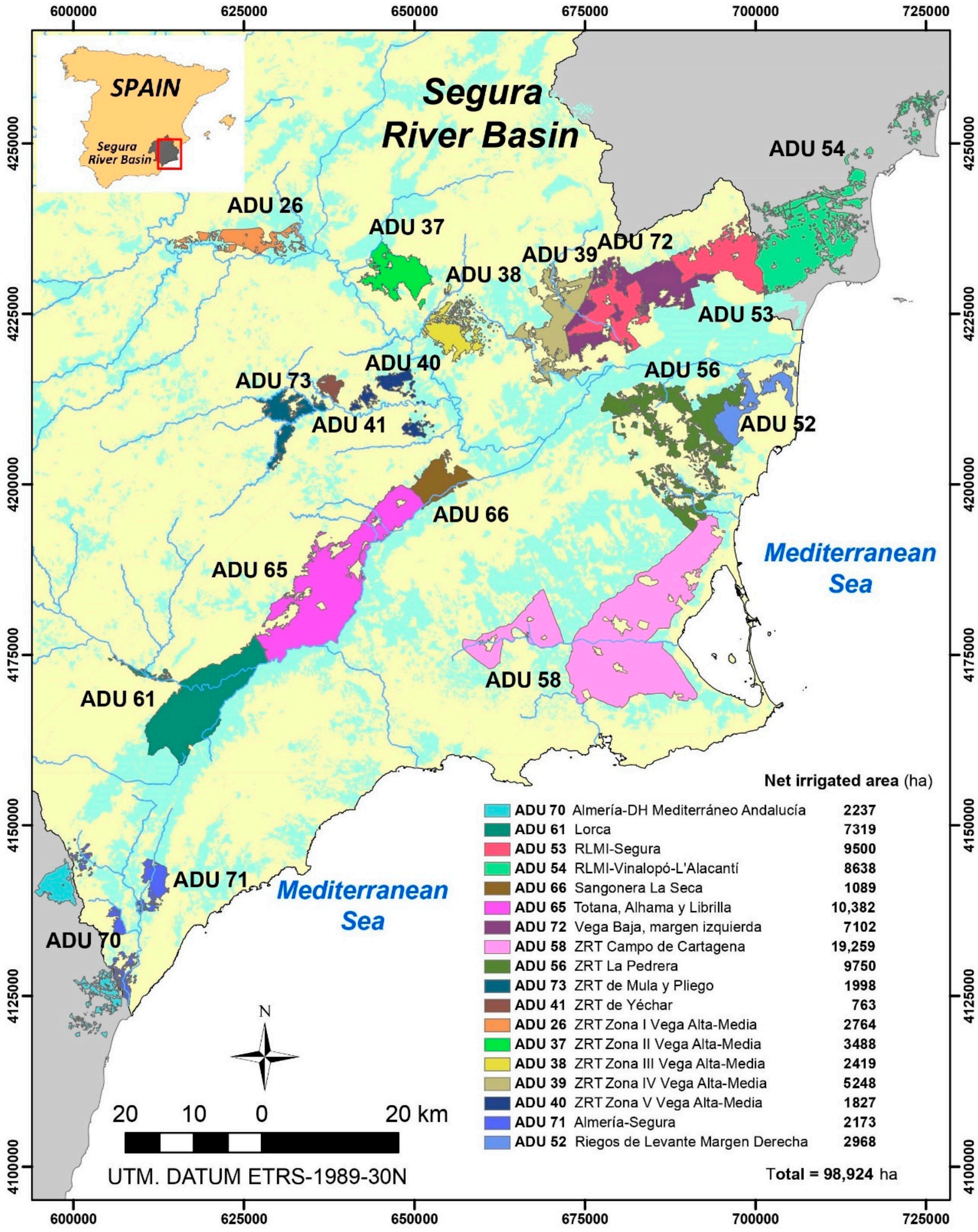

Figure 1. Study area and Agricultural Demand Units (ADUs) supplied by the Tagus–Segura water transfer (TSWT).

2.2. Water Supply Scenarios and Water–Energy Nexus

Irrigation activity is the main water and energy consumer in the production of irrigated crops under the agroclimatic conditions of the SRB. Agriculture in the SRB is supplied with water from different sources: superficial, ground, reclaimed, transferred and desalinated waters. The origin of the irrigation water is a key factor in the specific energy (kWh/m^3) associated with the supply [38]. In accordance, the following three water supply scenarios were considered:

- Concession scenario (WS0). This is a theoretical scenario corresponding to the irrigation rights recognised in the Hydrological Plan of the Segura Demarcation 2015/21 for the ADUs linked to the TSWT [35], without considering recent desalination concessions (13 Mm^3/year). The water resources' availability for this scenario are shown in Figure 2. The specific consumption associated with the supply in WS0 is 0.94 kWh/m^3.
- Current scenario (WS1). This corresponds to the irrigation rights recognised in the Hydrological Plan of the Segura Demarcation 2015/21 for the ADUs linked to the TSWT, adjusting the TSWT supply to its average value for the period 1979 to 2011 (196 Mm^3/year in origin and 176 Mm^3/year in destination [39]); and the DSW to current concessions (13 Mm^3/year included in the Hydrological Plan and 80 Mm^3/year assigned from the Torrevieja desalination plant, according to the Official State Gazette of 3 October 2019). This scenario is quite representative of the current situation due to the aforementioned progressive decrease in the transferred flow through the TSWT. The specific consumption associated with the supply in WS1 is 1.41 kWh/m^3.
- Substitution scenario of TSWT with seawater desalination (WS2). As shown in Figure 2, this is the same scenario as the Concession Scenario (WS0) but replacing 100% of the TSWT with DSW. It represents a hypothetical future scenario that could occur because of the multiple pressures on the TSWT. The specific consumption associated with WS3 is 2.78 kWh/m^3.

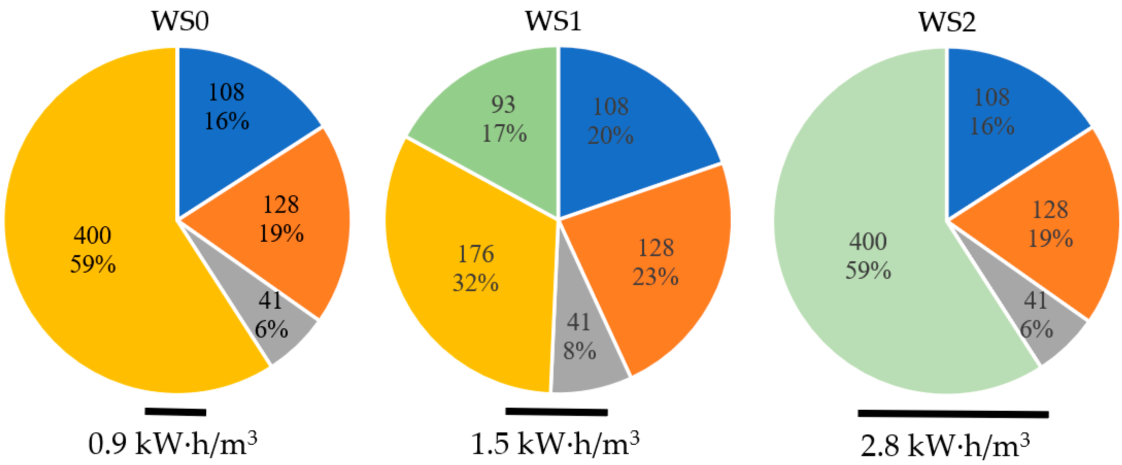

Figure 2. Mix of water sources (Mm^3/year) and the specific energy (kWh/m^3) by supply scenario. WS0: Concession scenario; WS1: Current scenario; WS2: Substitution scenario of TSWT with desalinated seawater (DSW).

The specific consumption values for each scenario were calculated based on the percentage of water provided by each source for this scenario (Figure 2) and their associated specific consumption (the calculation is included in Table S1 of the Supplementary Materials).

2.3. Main Crops Considered in the Study

Estimating GHG emissions for a crop requires all the information regarding the farming work and provided inputs, as well as the necessary infrastructure of the plot. The estimation of CO_2 removal usually requires samples to be taken from complete plant individuals in order to determine the carbon content of all their organs. Therefore, having all this information for all the crop species developed in the ADUs linked to the TSWT is not a straightforward process and is often only accessible for the most relevant crops. Nine crops were selected as being the most representative since they cover the largest area in the case studied.

The selected crops were organised into three groups (outdoor vegetables, citrus and non-citrus fruit) in order to comply with the classification of crops in the Hydrological Plan of the Demarcation of Segura 2015/21 for the description of the ADUs:

- Outdoor vegetables. This group is made up of artichoke, broccoli, lettuce and melon. Their covered area in the region represents 84.42% of the total cultivated vegetables area [40] (see Table S2 in the Supplementary Materials).
- Citrus. Lemon, mandarin and orange were considered. Their covered area in the region represents 97.78% of the total cultivated citrus area [40] (see Table S3 in the supplement for details).
- Non-citrus fruits (fleshy fruits). Apricot and peach were considered. Their covered area in the region represents 88.02% of the total cultivated non-citrus area [40] (see Table S4 in the supplement for details).

Table 1 shows the net area by crop group in the set of ADUs associated with the TSWT. The share was 27.81% for outdoor vegetables, 45.83% for citrus and 12.30% for non-citrus fruits, covering a total of 85.94% of the irrigated area in the case studied.

Table 1. Net area by crop group in the set of ADUs associated with the TSWT [34].

Crop	Surface Area (ha)	Percentage (%)
Citrus	45,339.5	45.83
Vegetables, outdoor	27,509.9	27.81
Non-citrus (fleshy fruit)	12,165.3	12.30
Olive	3638.3	3.7
Almond	2975.8	3.0
Cereals, winter	2161.8	2.2
Vegetables, protected	2198.1	2.2
Grapes, table	1704.5	1.7
Grapes, wine	864.8	0.9
Tuber (potato)	241.2	0.2
Cereals, spring (maize)	51.1	0.1
Lucerne	44.1	0.1
Cotton	29.3	0.1
Total	98,923.6	100.00

2.4. Carbon Footprint (CO_2 Balance)

The carbon footprint was determined as the difference between the GHG emissions related with farm operations and CO_2 (biogenic carbon) removal by crops. Throughout the study, the following sign criterion was considered: positive for carbon transfers from agricultural activity to the atmosphere and negative when transfers occur in the opposite direction. Therefore, GHG emissions have a positive sign, the removal of CO_2 has a negative sign and the balance sign is the result of the sum of those flows.

In order to determine GHG emissions related with farming operations, the LCA methodology was applied, following the protocols standardised by the ISO 14040/14044 standard series [29,30]. GHG emissions were estimated following the IPCC 2013 v 1.03 (time frame of 100 years) methodology from the Intergovernmental Panel on Climate Change [41] and expressed as $CO_{2\ eq}$ using the most recent IPPC emission factors [42].

The biogenic carbon dioxide fixation was estimated following ISO 14067 [43] and reported in terms of CO_2. According to ISO 14067, when calculating the carbon footprint for a product's entire life cycle all the emissions and removals (biogenic and fossil) must be considered, regardless of the crop cycle length. Details of biogenic carbon dioxide fixation by crops were obtained from Carvajal et al. [44], who presented information for most crops in SE Spain. The carbon sequestration in the soil could not be quantified and hence considered due to current lack of data, like the actual influence of tillage, organic amendments and crop rotation on the carbon storage.

2.4.1. Calculation of GHG Emissions by Life Cycle Assessment (LCA) Methodology

In order to determine GHG emissions related with farming operations, the LCA results obtained in a manuscript recently published by the authors [33] were considered. LCA was used to quantify the environmentally relevant flows of the most important fruit and vegetable production systems in SE Spain from several perspectives: depletion of elements and fossil fuels, acidification and eutrophication hazards, global warming potential and use of water resources. An LCA sensitivity analysis was used in this study to estimate the variation in the GHG emissions, considering the specific energy from the supply scenarios defined above (Section 2.2).

The functional unit was the cultivation of one hectare, throughout one year. The crop cycle length was one year for citrus (lemon, orange and mandarin) and non-citrus (apricot and peach) woody crops, and artichoke; six months for broccoli; and four months for lettuce and melon. In order to compare results between crops throughout one year, the following five annual crop rotations of outdoor vegetables were considered, because they are the most frequent and representative in the study area (information provided by the "Campo de Cartagena" Irrigation District, www.crcc.es): (1) lettuce–lettuce; (2) lettuce–broccoli; (3) lettuce–melon; (4) broccoli–melon; (5) artichoke. We considered the average value obtained from those crop rotations as being the annual value per hectare for outdoor vegetables.

More detailed information regarding the LCA carried out can be found in the Supplementary Materials, including (i) the system boundaries for the cradle-to-gate production of vegetable and woody crops (Figure S1), (ii) the description of the agricultural stages (Table S5) and (iii) the LCA inventory for the studied crops (Tables S6 and S7). In addition, the surface area by crop group in each ADU (Table S8) and the annual values of the carbon balance in each ADU (Tables S9 and S10) are provided.

2.4.2. Calculation of CO_2 Removal by Crops

The biogenic carbon dioxide fixation by crops was obtained from the study by Carvajal et al. [44], which analysed the potential for CO_2 removal for the main agricultural and forestry species in the region. Table 2 shows the carbon removal values (t CO_2/ha) of the crops under study.

Table 2. Annual values of CO_2 fixation (kg CO_2) per plant and per hectare and planting density (plant/ha) of the main vegetables and woody crops cultivated in the region [43].

Crop Group	Crop	CO_2 Fixation (kg CO_2/Plant)	Planting Density (Plant/ha)	CO_2 Fixation (t CO_2/ha)
Outdoor vegetables	Artichoke	−1.854	7000	−12.98
	Broccoli	−0.239	35,000	−8.37
	Lettuce	−0.130	65,000	−8.45
	Melon	−0.802	10,000	−8.02
Citrus	Lemon	−106.93	280	−29.94
	Mandarin	−31.11	420	−13.06
	Orange	−49.35	420	−20.73
Non-citrus (fleshy fruit)	Apricot	−84.49	204	−17.24
	Peach	−49.77	570	−28.37

2.5. Extrapolation of Results to ADUs Supplied by the TSWT

A Geographic Information System (ESRI ArcGIS) was used to extrapolate the values previously obtained to the entire target area. The steps followed in the extrapolation process can be summarised as follows:

1. Determination of the annual values of GHG emissions, CO_2 removal and carbon balance for each crop group and water scenario. For the "citrus" and "non-citrus" fruit groups the value was calculated using the weighted average by the area of each crop of the selected group in the region (see Tables S3 and S4 for details). In the case of the "outdoor vegetables" group, the average value obtained from the five most frequent and representative crop rotations in the study area was considered as an annual value per hectare (Section 2.4.1).
2. Determination of the weight of each crop group in each ADU. The percentages that each group of crops represents in each ADU were considered (data included in Table S8 of the Supplementary Materials). Then, the net area corresponding to the crop groups was calculated, increasing it in proportion to its magnitude until the total net area of each ADU was reached.
3. Determination of the total (t $CO_{2\,eq}$/year) and specific (t $CO_{2\,eq}$/ha-year) annual GHG emissions per ADU and water scenario. From the GHG emissions values calculated for each crop group, the value corresponding to each ADU was obtained by multiplying that value by the weight of the crop group in the ADU (t $CO_{2\,eq}$/ha-year) and by the net area of the ADU (t $CO_{2\,eq}$/year). This process was repeated for each water scenario.
4. Determination of the total (t CO_2/year) and specific (t CO_2/ha-year) annual CO_2 removal and carbon balance per ADU. The same procedure described in step 3 was followed.
5. Aggregation and graphic representation of the entire study area results for each water scenario. The estimation of the total and specific annual values of GHG emissions, CO_2 removal and carbon balance were carried out by adding the values obtained for each ADU and water scenario. Finally, those values were graphically presented to show their spatial trends.

3. Results and Discussion

3.1. Carbon Balance of the Selected Crops

The GHG emissions, CO_2 removal and carbon balance for the selected crops and scenarios are presented in Figure 3. Overall and regardless of the scenario, the vegetables show greater variability of GHG emissions than the woody crops. The cultivation of vegetables annually emitted 7.96 ± 2.73, 9.18 ± 3.31 and 12.77 ± 5.03 t $CO_{2\,eq}$/ha for scenarios WS0, WS1 and WS2, respectively, whereas the figures for the woody crops were 8.37 ± 0.98, 9.37 ± 1.03 and 12.30 ± 1.21 t $CO_{2\,eq}$/ha. For both the vegetables and the woody crops, the greatest GHG sources came from irrigation, field operations and fertilisers. In the case of vegetables, those stages amounted to 88.3, 89.9 and 92.0% of the total emissions in WS0, WS1 and WS2, respectively. The annual values for woody crops were somewhat similar: 91.7, 92.6 and 94.4%, respectively. Our results about the important contribution of irrigation practices in GHG emissions were in agreement with those reported by other authors for the Mediterranean region. Persiani et al. [45] found that the highest energy-consuming inputs for a cauliflower–lettuce rotation in southern Italy were irrigation followed by fertilisers; and the highest GHG emissions were for water and fertilisers. In this respect, Martin-Gorriz et al. [33] proposed and evaluated mitigation strategies to reduce GHG emissions for crops in SE Spain. The most promising impact-mitigation action was the replacement of mineral fertiliser with manure, which offered potential GHG emissions reductions of up to 10 and 21% for vegetable and woody crops, respectively.

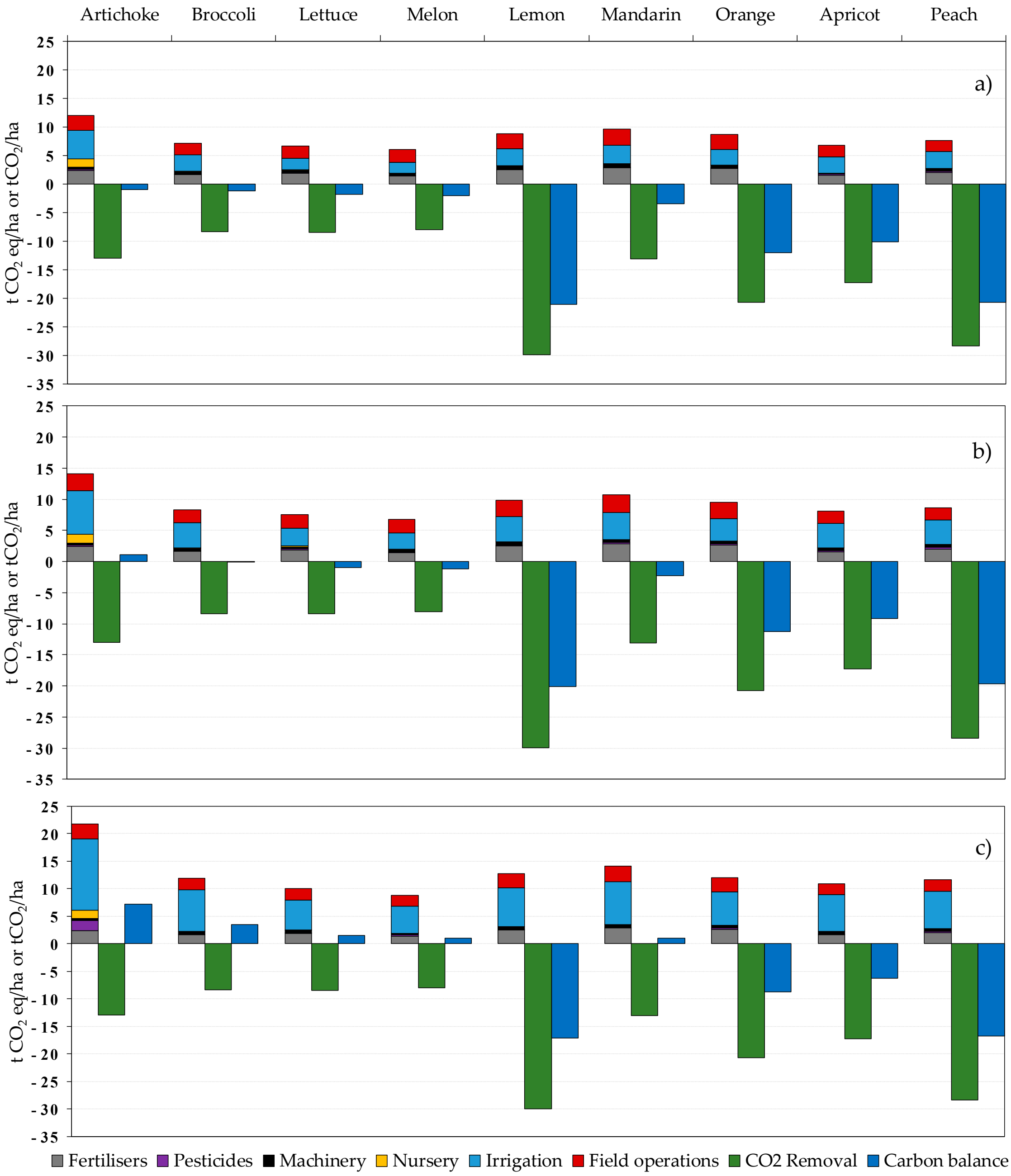

Figure 3. Greenhouse gas (GHG) emissions by crop (expressed as the contribution by stages: fertilisers, pesticides, machinery, nursery, irrigation and field operations), CO_2 removal and carbon balance for the three scenarios; (**a**) WS0, (**b**) WS1 and (**c**) WS2.

With regard to CO_2 removal, the annual values for the three scenarios were -9.46 ± 2.36 and -21.87 ± 7.21 t CO_2/ha for the vegetables and the woody crops, indicating that the outdoor vegetables fixed a notably smaller amount than the woody crops. This can be explained by the higher leaf area index and the longer use of the land in woody crops, which stay and fix carbon throughout the whole year. Artichoke was the exception, with its CO_2 removal value being 50% higher than that for the rest of the vegetables, as shown in Figure 3.

In the Concession Scenario (WS0, Figure 3a), the annual emissions from the vegetables ranged from 6.05 t $CO_{2\,eq}$/ha (melon) to 12.01 t $CO_{2\,eq}$/ha (artichoke). Irrigation accounted for 36.7%, which can be attributed to the fossil fuel combustion to produce electricity to transport water; fertilisers accounted for 23.3%, which is attributed to the electricity used for its production; whilst field operations accounted for 28.3%, associated to the diesel consumption by machinery. In the case of the woody crops, the emissions ranged from 7.12 t $CO_{2\ eq}$/ha (apricot) to 9.60 t $CO_{2\ eq}$/ha (mandarin). In this case, irrigation, fertilisers and field operations represented 35.2, 27.7 and 28.9%, respectively. In this scenario, all the crops acted as a CO_2 sink. On average, the balance for the woody crops was about nine times more favourable than for the vegetables (−13.49 ± 7.48 vs. −1.49 ± 0.46 t CO_2/ha). The lemon crop presented the most negative balance and artichoke had the least negative balance.

The current scenario (WS1, Figure 3b) showed a rise in specific energy consumption from 0.94 kWh/m^3 in WS0 to 1.41 kWh/m^3, which implies an increase in the emissions for all the crops. For the vegetables, such increases ranged from 12% (lettuce and melon) to 17% (artichoke and broccoli). In WS1, irrigation, fertilisers and field operations accounted for 45.0, 20.2, 24.6% GHG emissions, respectively. In the case of the woody crops, such increases ranged from 12% (citrus) to 14% (fleshy fruits). In this case, irrigation accounted for 42.1%, fertilisers for 24.7% and field operations for 25.8% of the total GHG emissions. All the crops continued to act as a CO_2 sink, except for artichoke and broccoli. Artichoke became a source of carbon (1.09 t CO_2/ha, i.e., its farming practices emitted more CO_2 into the atmosphere than that captured by the crop), whereas broccoli presented an almost neutral balance (−0.06 t CO_2/ha). On average, the balance was about 45 times more favourable for the woody crops than for the vegetables (−12.50 ± 7.52 vs. −0.27 ± 1.03 t CO_2/ha). Lemon was again the crop with the most negative balance.

Regarding the hypothetical substitution of TSWT with DSW (WS2, Figure 3c), the specific energy reached 2.78 kWh/m^3 and the GHG emissions were again higher. For the vegetables, lettuce and melon GHG emissions increased by 50% (lettuce–melon rotation) to 68% (artichoke–broccoli rotation) compared to WS0. Of the total GHG emissions, irrigation accounted for 60.5% of GHG emissions, which is attributed to the fossil fuel combustion for electricity to produce and transport water; fertilisers accounted for 14.5% and field operations for 17.0%. In the case of the woody crops, emissions increased range from 45% (citrus) to 53% (fleshy fruits). In this case, irrigation accounted for 55.8%, fertilisers for 18.8% and field operations for 19.7% of the total. In WS2, only the woody crops continued to be net carbon fixers (−9.57 ± 7.62 t CO_2/ha), whereas all the vegetables acted as a CO_2 source (3.31 ± 2.75 t CO_2/ha), with artichoke being the crop with the highest carbon balance (7.14 t CO_2/ha) and melon the one with the lowest (1.05 t CO_2/ha).

The annual values of GHG emissions, CO_2 removal and carbon balance per crop group and scenario are summarised in Table 3. The carbon balance became less favourable for the environment as the specific energy (kWh/m^3) of the water supply intensified due to the progressive incorporation of DSW (WS0 → WS1 → WS2). The per-hectare analysis showed that the GHG emissions for the outdoor vegetables were 60% higher than for the woody crops in WS0. This is mainly attributed to the higher implementation of inputs in the vegetables [33]. Such a percentage increased up to 70% in WS2 due to the higher use of DSW for irrigation. Thus, CO_2 removal by the vegetables was always lower than that of the woody crops. As a result of both behaviours, the annual carbon balance of the vegetables was 6 (WS0) to 17 (WS2) times lower than for the woody crops. This circumstance means that outdoor vegetables went from being a carbon sink in WS0 to being a carbon source in WS2. Therefore, the woody crops were demonstrated to be more effective in mitigating climate change than the vegetables, but on the other hand, they are riskier crops for farmers since they are more sensitive to suffering drought in the long term [46].

Table 3. Annual values of GHG emissions, CO_2 removal and CO_2 balance per crop group and scenario.

Water Scenario	Crop Group	GHG Emissions (t $CO_{2\,eq}$/ha-Year)	CO_2 Removal (t CO_2/ha-Year)	CO_2 Balance (t CO_2/ha-Year)
W0	Outdoor vegetables *	13.02	−15.91	−2.89
	Citrus	8.91	−25.56	−16.65
	Non-citrus fruit	7.47	−24.08	−16.60
W1	Outdoor vegetables *	14.90	−15.91	−1.01
	Citrus	9.91	−25.56	−15.65
	Non-citrus fruit	8.46	−24.08	−15.62
W2	Outdoor vegetables *	20.43	−15.91	4.52
	Citrus	12.87	−25.56	−12.69
	Non-citrus fruit	10.96	−24.08	−12.72

* Average values for the most frequent annual crop rotations: (1) lettuce–lettuce; (2) lettuce–broccoli; (3) lettuce–melon; (4) broccoli–melon; (5) artichoke. Note that the values for each crop are provided in Figure 3.

3.2. Carbon Balance by Agricultural Demand Units (ADUs)

Once the annual values of carbon balance per crop group (Table 3), as well as the weight of each group in the ADUs were estimated (Table S8), the total (t CO_2/year) and the specific (t CO_2/ha-year) annual carbon balances were calculated within each ADU for the selected scenarios (Figure 4). The results are given in Tables S6 and S7 for total and specific annual values, respectively.

Figure 4a,c,e represent the total GHG emissions, CO_2 removals and carbon balance for the WS0, WS1 and WS2 scenarios, respectively. For WS0 and WS1, all ADUs had a negative carbon balance, which demonstrates the CO_2 sink role of irrigated agriculture in the study area under concessional and current water supply conditions. The absolute magnitude of the carbon balances in Figure 4a,c,e were mainly driven by ADU size, though crop composition played a role (as shown more clearly in 4b, 4d and 4f). The relative magnitude of an individual ADU among the three scenarios showed the increasing rate of GHG emissions with the progressive incorporation of DSW. Consequently, the total carbon balance in each ADU lessened when passing from WS0 to WS1 and lessened still further for WS2, where ADUs 61, 70 and 71 presented a positive total carbon balance, i.e., they became sources of carbon. Therefore, the substitution of TSWT supply with DSW can change the role of irrigated agriculture from being a carbon sink to being a carbon source under certain conditions, which are analysed below.

Figure 4b,d,f represent the specific (per hectare) carbon balance for WS0, WS1 and WS2 scenarios, respectively. A spatial trend of the specific carbon balance value could be appreciated for all scenarios. It clearly decreased from north to south, but also varied more subtly from inland to the coast. This variation is related to the crop groups prevailing in the ADUs (Table S8). Since the southern and coastal zones in the study area present milder winter conditions and warmer springs, they are far more suitable for winter outdoor vegetables (broccoli and lettuce) and for early muskmelon crops during the spring–summer season, for which it is desirable to advance the cultivation date looking for better market prices. Therefore, the ADUs located in the southern and coastal areas were those with a higher proportion of outdoor vegetables (ADUs 58, 61, 70 and 71 had from 58 to 79% of total surface area) and, consequently, those with a less favourable specific carbon balance. On the contrary, the woody crops were those with a more favourable specific carbon balance (Table 3) and they predominate in inland and northern ADUs. Non-citrus trees (fleshy fruits) were those that better tolerated winter cold, which is essential for the proper development of their annual fruiting cycle, so they are mainly located in more inland ADUs (ADUs 26, 37, 38, 40, 41 and 73 had from 54 to 86% of total surface area), justifying their higher specific carbon balance values. Finally, citrus predominate in the northern area (ADUs 39, 52, 53, 54, 65 and 72 had from 53 to 83% of total surface area), where mild conditions throughout the year (coastal effect leading to the absence of frost in winter and very high temperatures in summer) favour their productive cycle. Therefore, the spatial trend of the specific carbon balance value was related to the prevailing location of crops, explaining the positive total and specific carbon balances of southern ADUs in WS2. The latter became a carbon source due to the predominance of the only crop group presenting a positive CO_2 balance: outdoor vegetables. It should also be highlighted that citrus, having shown one of the most negative carbon balances in all scenarios and hence being one of the most environmentally sustainable crops, is also one of the crops with a lower economic net margin per cubic metre, as reported in Martínez-Alvarez et al. [23], thus pinpointing that citrus is the crop whose economy would be most affected by the implementation of an agricultural supply where DSW was the predominant water source.

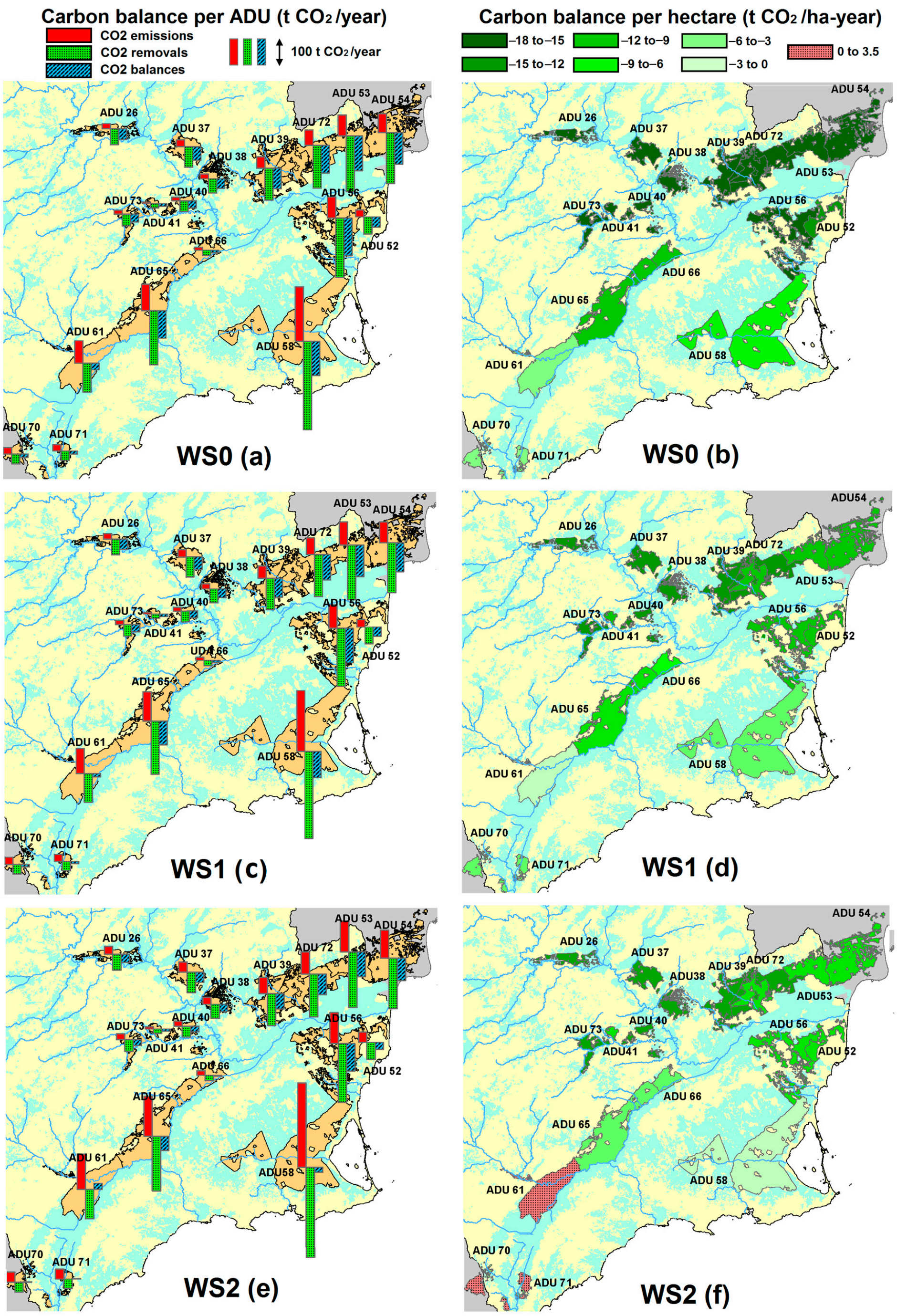

Figure 4. Total carbon balance per ADU (t CO_2/year; **a**,**c**,**e**) and specific carbon balance (t CO_2/ha-year; **b**,**d**,**f**) within each ADU for the considered scenarios: WS0 (**a**,**b**), WS1 (**c**,**d**) and WS2 (**e**,**f**).

3.3. Carbon Balance of the Irrigation Lands Supplied by the TSWT

Table 4 shows the total and specific GHG emissions, CO_2 removal and carbon balance for the net irrigated area associated with the TSWT (98,923.6 ha), obtained by adding the values for each ADU and scenario.

Table 4. Total and specific annual GHG emissions, CO_2 removal and carbon balance for the net irrigated area associated with the TSWT for the considered scenarios.

Scenario	GHG Emissions	CO_2 Removal	CO_2 Balance
WS0			
Total (t $CO_{2\,eq}$/year)	991,744	−2,177,828	−1,208,084
Specific (t $CO_{2\,eq}$/ha-year)	9.61	−22.57	−12.96
WS1			
Total (t $CO_{2\,eq}$/year)	1,118,748	−2,177,828	−1,081,080
Specific (t $CO_{2\,eq}$/ha-year)	10.84	−22.57	−11.73
WS2			
Total (t $CO_{2\,eq}$/year)	1,492,552	−2,177,828	−707,276
Specific (t $CO_{2\,eq}$/ha-year)	14.47	−22.57	−8.10

Overall, the results show that the irrigated area associated with the TSWT acted as an important carbon sink regardless of the scenario. This decreasing capacity as a carbon sink was inversely proportional to the increase in specific energy due to the growing percentage of DSW in the irrigation mix (from 0.94 kWh/m^3 in WS0 to 2.78 kWh/m^3 in WS2). In fact, irrigation was responsible for 36% of the $CO_{2\,eq}$ emissions in WS0, with that figure increasing to 45.0 and 60.5% in the WS1 and WS2 scenarios, respectively.

These figures indicate that, although the incorporation of massive DSW supply to irrigated agriculture can enhance its resilience in the face of water shortages, such a strategy does reduce its mitigating role against the increasing CO_2 concentration in the atmosphere. Improved sustainability of irrigated agriculture is needed to compensate for this undesirable effect. This aspect is discussed below.

4. Adaptation Strategies to Increase Sustainability

At the EU level, agriculture has been responsible for 10% of the GHG emissions in the last decade [47]. That figure reaches 12% in the case of Spain [48]. Irrigation is currently responsible for 45.0% of the GHG emissions in the irrigation districts linked to the TSWT (WS1 scenario), although this could increase to 60.5% in the near future (WS2). Some of the following strategies can be considered for dealing with that potential increase to foster sustainability of the DSW agricultural use:

1. *Controlled blending of DSW with other water sources*. This has been documented in several countries, including Israel [49–52]; Spain [27,53–55]; Mexico [56,57]; USA (California) [58–60]; and Australia [61]. In Israel for example, blending 36% of DSW with other water sources (groundwater, surface water and brackish water) reduced GHG emissions by 53% compared to 100% DSW [52]. In the case of *La Marina* seawater desalination plant in Almería (south of Spain), mixing the DSW with groundwater did help remineralise DSW whilst significantly reducing the associated environmental impact [27]. In SE Spain, Martínez-Alvarez et al. [62] evaluated the impact of irrigation with DSW on farming costs and fertiliser requirements for different crops, concluding that blending DSW and conventional water at a 50% rate notably reduced the operational costs (mainly linked with energy consumption) and the fertiliser application, although that study did not estimate its associated positive environmental impact.
2. *Increasing renewable energy sources in electricity mix production.* Reducing GHG emissions associated with the electricity mix to produce DSW is another important strategy to increase the sustainability of DSW for irrigation. Of all industry sectors, electricity is responsible for the largest fraction (25%) of global anthropogenic GHG emissions [1]. The share of renewable energies in global electricity generation approached 26% in

2018 [63] and reached 32% in the European Union [64]. In September 2020, the European Commission proposed raising the 2030 GHG emission reduction target to at least 55% compared to 1990. Achieving this target requires: (i) an increased share for renewable energy of at least 32% and (ii) an improvement in energy efficiency of at least 32.5% [65]. In line with these policy targets, the integration of renewable energy into DSW production may substantially reduce its carbon footprint. In fact, Shahabi et al. [66] indicated that seawater desalination plants powered with renewable energy can achieve a 90% reduction in GHG emissions. Numerous other authors have stressed the importance of increasing renewable energy in the production of electricity to improve the sustainability of horticulture [33,67,68]. Torrellas et al. [67] indicated that the current overexploitation of aquifers in water-scarce areas, such as SE Spain, has promoted the use of non-conventional water resources such as DSW. That is why electricity consumption has increased around eightfold in these cultivation cases, using 100% of DSW for irrigation. Therefore, renewable energies are important in counterbalancing farming electricity consumption increases, as Martin-Gorriz et al. [55] highlighted in a study on greenhouse tomato production irrigated with DSW, where a 53% increase in the use of renewable energy in the production of electricity led to a 17% reduction in GHG emissions.

3. *Improving water use efficiency*. Improving irrigation water use efficiency contributes to cutting down the energy consumption for water management and irrigation in the same proportion. In this sense, in the last 10 years the water consumption by irrigation in Spain fell by 15% [69]; and in 2018 the water volume applied by drip irrigation in Spain was 53%, reaching 86% in the case of the ADUs linked to the TSWT [70]. These data show the commitment of practitioners (farmers and technicians) in the study area to a more sustainable and efficient agriculture. On the one hand, advances in irrigation systems as well as new technologies, such as wireless sensor networks and remote sensing tools, can be applied to further improve irrigation efficiency in vegetables and woody crops [71,72]. Consequently, it is possible to reduce energy consumption whilst improving water use efficiency through comprehensive irrigation management. In such a way, Gonzalez Perea et al. [73] achieved a 15% reduction in energy consumption by implementing more efficient irrigation and water management practices, with no significant yield reduction. Qureshi [74], improving on-farm irrigation management, achieved a 40% reduction in CO_2 emissions in Pakistan. Cvejic et al. [75] also reduced the irrigation-volume consumption by 25% and the GHG emissions by 24%, through the adoption of irrigation-decision support systems tools in Vipava Valley (Slovenia). On the one hand, prioritising crops with lower water footprints and higher dietary efficiency, provided they are still profitable for farmers, is key to reduce the water demand. A recent study looking at the water footprint of 50 Mediterranean crops (including most of the crops of this study) demonstrated the importance of selecting agro-systems not only based on the irrigation efficiency but also accounting for the crop dietary efficiency as well as the economic productivity and efficiency [76].
4. *Adoption of soil carbon sequestration practices*. Organic amendments, residue incorporation, reduced tillage or crop rotation can reach 4 per mille or even higher soil carbon sequestration rates [77]. Organic amendment additions represent direct inputs of organic carbon into the soil systems. In Mediterranean woody crops a combination of inter-row plant covers with organic amendments like pruning residues have been reported to be a successful carbon sequestration practice [78]. For Mediterranean vegetable crops, rotations that include agro-ecological service crops combined with the addition of green manure have been demonstrated to be very efficient in terms of carbon sequestration [79]. Tillage reduction implies higher crop residue retention and lower fuel consumption [80,81], but it is environmentally beneficial only if not replaced by polluting herbicides. Overall, the key aspect here is the fact that the CO_2 captured from the atmosphere and incorporated into the plants stays within in the agro-systems with these practices, rather than being released back to the atmosphere.

5. Conclusions

The present study estimates the carbon footprint of the irrigated lands supplied by the TSWT in SE Spain, quantifying their carbon balance as the difference between GHG emissions from agricultural activities and CO_2 removals due to planted crops. The study focuses on how the source of the water supply for irrigation can influence the GHG emissions of farming activity and, consequently, its carbon footprint. In order to determine this, the irrigated agriculture of the study area has been analysed under three water supply scenarios involving a progressive substitution of the TSWT supply by DSW.

Our results show that GHG emissions for crops depend largely on water sources and, consequently, their carbon footprint. Among the crops, the woody crops have a more favourable specific carbon balance (per hectare) than outdoor vegetables from an environmental perspective. This can be mainly attributed to the lower implementation of inputs in woody crops. The incorporation of DSW to crop irrigation enhances the energy consumption linked to the water supply, which could change the role of outdoor horticultural crops from a carbon sink to a carbon source.

The irrigated area associated with the TSWT acts as an important carbon sink, regardless of the scenario. However, its sink capacity diminishes in proportion to the increase in the specific energy of water supply, due to the growing percentage of DSW in the irrigation mix. In this sense, a complete substitution of the TSWT supply by DSW (WS2) might increase GHG emissions by up to 50% and reduce the carbon balance by 41%.

This trend is particularly marked in some irrigation districts where outdoor vegetables are the prevailing crops; they become carbon sources with a positive net carbon balance (CO_2 removals < $CO_{2\,eq}$ emissions) in the hypothetical scenario of complete substitution of the TSWT supply by DSW (WS2). Therefore, substituting the TSWT supply with DSW can change the role of irrigated agriculture from a carbon sink to a carbon source under specific circumstances, such as the prevalence of outdoor horticultural crops. Moreover, the spatial trend of the specific carbon balance is also related to the prevailing location of the crops; the northern and inland irrigation districts, where the agroclimatic conditions are more suitable for woody crops (citrus and fleshy fruits), are proved to be more favourable than the southern irrigation districts, where milder winters favour the production of outdoor horticultural crops.

Our results show that, although the incorporation of DSW supply to irrigated agriculture can enhance its resilience in the presence of water shortages, thereby supporting the associated socioeconomic development, it decreases its CO_2 sink role and consequently, its climate change mitigating potential. To compensate for this, some potential ways to improve the sustainability of the agricultural DSW use are proposed: blending DSW with other water sources; boosting the renewable energies rate in the electricity mix production; a comprehensive improvement of water use efficiency; adopting soil carbon sequestration practices. Farmers and technicians in the study area are becoming increasingly aware of these measures, but their application should be encouraged by agricultural policies to achieve a more efficient and sustainable agriculture.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4395/11/2/351/s1: Table S1. Water resources and specific energy contributions to irrigation mix by scenario. Table S2. Surface area and percentage of outdoor vegetables in the region in 2017. Table S3. Surface area and percentage of citrus in the region in 2017. Table S4. Surface area and percentage of non-citrus (fleshy fruit) in the region in 2017. Figure S1. System boundaries for cradle-to-gate production of vegetable and woody crops (citrus fruits and non-citrus trees). Table S5. Agricultural stages of Life Cycle Assessment. Table S6. Life Cycle Inventory for the vegetable crops of the study. Table S7. Life Cycle Inventory for the woody crops (citrus and non-citrus trees) of the study. Table S8. Percentage of surface area by crop group in each ADU. Table S9. Total annual values of carbon balance in each ADU for the considered scenarios. Table S10. Annual values of carbon balance per hectare in each ADU for the considered scenarios.

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