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Is seasonal households' consumption good for the nexus carbon/water footprint? The Spanish fruits and vegetables case

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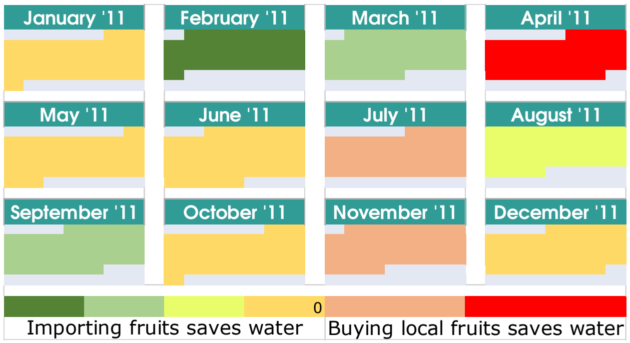

ABSTRACT

Proximity and in-season consumption criteria have been suggested as solutions for fruits and vegetables consumers to drive the economy to a more sustainable development. Using a new concept, seasonal avoided footprint by imports, we disentangle the role of period and country of origin. Although, as a general rule, consumers could reduce its footprint by choosing domestic produce, this is not always the case. Due to the high efficiency of Spanish domestic production in terms of both CO2e and water use (except for scarce water), imports from some regions, like Africa (green beans, pepper, tomato, banana, strawberry, oranges), contribute to significantly increase both water and carbon impacts. However, a monthly-basis analysis shows unsustainable hotspots for domestic production. Importing from France (apple, potato) or Portugal (tomato, strawberry) reduces both footprints, so Spanish local consumption would be bad for the environment. Hotspots are mainly concentrated in scarce water and, especially, for out-of-season vegetables during eleven months a year (savings up to 389%), nine months for out-of-season fruits and five months for in-season fruits. The results suggest the difficulty to generalize an easy environmental recommendation based on buying local fruits and vegetables: consumption must be analyzed on monthly/seasonal, products and countries basis.

I. INTRODUCTION

Globalization has allowed for the year-long availability of a wide variety of fruits and vegetables, as Southern Hemisphere products can quickly reach northern countries' consumers. Therefore, consumption has become greatly independent of seasons and offers an advantage to consumers that originates the environmental impact that we propose to quantify. Consumers in Spain spend 14.8% of their total expenditure on food, and 2.9% is spent specifically on fruits and vegetables[1]. The related carbon footprint ranges from 9.2 to 13.8 tCO_2 equivalent (CO_2e) per capita (of which food is responsible for 23% and plant-based food for 2.8%), depending on the region[2].

While most drives to promote local in-season fruits and vegetables are based on the argument that they are healthier and of better quality[3], the literature on food miles[4] and the impact of trade on the environment could also be used for promotion. This statement emphasizes the importance of the transport stage in the emissions of the whole cycle of food, disregarding the importance of the production and complementary processes that have been found to be more polluting[5-7]. Due to environmental efficiency and/or use of fewer resources, it is not always the case that the environmental impact from domestic production is lower[8, 9] than that in other countries for fruits and vegetables that are in-season there. Innovative production, storage and transportation technologies are also challenging previous ideas about the potential reduction of environmental impacts due to in-season production and consumption.

The study of environmental impacts from different patterns of food consumption is a very relevant topic in the recent literature, including studies that use life cycle assessment (LCA) or input-output methodology[10-13]. LCA focuses on particular food types[6, 14-16] to calculate the impact of importing out-of-season products. Conclusions in this previous literature appear to point to a minimal consensus that although no large environmental benefits are expected by seasonal consumption[17], they could be important if seasonality is combined with local production[6,7], particularly in countries with high agriculture efficiency[18]. Bottom-up LCA studies of specific products have the advantage of including very detailed information but show certain disadvantages: 1) comparisons between studies are complex, as the environmental impact depends crucially on the production technique (for example, greenhouses) and the scope reached, not only on the season of the year; and 2) the focus of these studies on a small portion of the total food expenditure makes it difficult to obtain more general conclusions. To evaluate the potential impact of changing consumption of domestic and seasonal produce, a more encompassing method is required[17]. An input-output methodology combined with actual data on seasonal food purchases appears to be an appropriate alternative.

The two main questions addressed by this paper are the following: What would the effect on the water and carbon footprint be if the Spanish households substituted imported fruits and vegetables for local production? Is the impact similar for in-season and out-of-season local production? These questions are encountered by developing, for the first time to our knowledge, an environmentally extended multiregional input-output model (MRIO) for the monthly demand of out-of-season imported fruits and vegetables. We introduce the innovative concept of seasonal avoided footprint by imports (SAFM); therefore, we compare emissions from imported and domestic produce avoided by these imports on a monthly basis. This new element allows us to assess the emissions and water content of our current consumption of fresh fruits and vegetables given their composition and country of origin and compare them to the emissions and water use of the alternative domestic crops. While this comparison can be assimilated to the concept of a balance of avoided emissions[19-25] or water use, there is a principal novelty in terms of seasonality. The proposed measure considers fresh fruits and vegetables that may not be locally available at that time of the year (or that may require more costly and less environmentally friendly production technologies, such as greenhouses) and that need to be consumed within days. Using technology data from input-output tables does not allow us to distinguish among different techniques for each fruit; however, we obtain information on the average technology used in our imported fresh products depending on their country of origin by month.

Another interesting aspect of our analysis is the consideration of two different types of environmental impact, as we consider both CO_2e emissions and water use. This procedure emphasizes the water-energy-food nexus, since these three elements are inextricably linked in a complex manner such that human decisions affect the three differently. The previous literature on this nexus (see for the UK[26] and for China[27]) notes that agricultural products occupy the top positions in terms of water and energy footprints. It is also relevant that as different alternative production techniques substitute certain inputs for others, the effects by footprint type are different. The production systems differ in input requirement intensity. However, in many cases, agricultural produce occurs in locations with sufficient water resources that need the use of energy to produce artificial heat, while locations with adequate climatic conditions frequently require water inflows in a water-scarcity context[28-30]. Clear trade-offs appear, in particular between water use and energy (and therefore GHG), such that conclusions cannot be based on standalone indicators.

II. METHODS AND MATERIALS

II.1. MRIO model and seasonal MRIO models

On the basis of an MRIO, environmental extensions have been used to evaluate the impact of international trade on different factor contents[31]: CO_2[32, 33], water[34], materials[35], energy[36], and nitrogen[37]. The usual expressions of an environmentally extended MRIO for a global economy aggregated to two regions (*r, s*) and two sectors of activity (*i, j*), in time period *t*, normally a natural year, is as follows in expression (1):

$$F = \begin{pmatrix} f_i^r & 0 & 0 & 0 \\ 0 & f_j^r & 0 & 0 \\ 0 & 0 & f_i^s & 0 \\ 0 & 0 & 0 & f_j^s \end{pmatrix} \begin{pmatrix} L_{ii}^{rr} & L_{ij}^{rr} & L_{ii}^{rs} & L_{ij}^{rs} \\ L_{ji}^{rr} & L_{jj}^{rr} & L_{ji}^{rs} & L_{jj}^{rs} \\ L_{ii}^{sr} & L_{ij}^{sr} & L_{ii}^{ss} & L_{ij}^{ss} \\ L_{ji}^{sr} & L_{jj}^{sr} & L_{ji}^{ss} & L_{jj}^{ss} \end{pmatrix} \begin{pmatrix} y_i^{rr} & 0 & y_i^{rs} & 0 \\ 0 & y_j^{rr} & 0 & y_j^{rs} \\ y_i^{sr} & 0 & y_i^{ss} & 0 \\ 0 & y_j^{sr} & 0 & y_j^{ss} \end{pmatrix} \qquad (1)$$

where F denotes environmental factors embodied in production by the world economy; and $\hat{f}$ is the diagonal matrix of environmental factor coefficients. A is defined as the matrix of input coefficients, which we can decompose in A^{rr}, the matrix of domestic production coefficients of country r and A^{rs} the matrix of imported coefficients from country r to country s. The diagonalized matrix of final demand is $\hat{y}$, which includes the diagonalized vector $\hat{y}^{rr}$ of the domestic final demand and the diagonalized vector $\hat{y}^{rs}$ of the final exports of country r to country s. Utilizing the identity matrix I, reading by columns, the Leontief inverse is $L = (I - A)^{-1}$, which captures all direct and indirect inputs required for providing a monetary unit of final demand of country r all over the world; this process is done in the same country r by L^{rr} in the main diagonal and in other regions s and by L^{sr} in the off-diagonal positions.

However, evaluating a seasonal balance requires economic and environmental information regarding a unit of time that coincides with the season of fresh fruits and vegetables in which the products analyzed are produced. Constructing a full-season MRIO from an annual MRIO would require disaggregating the annual data into seasonal information (see SI for a detailed explanation): a) final demand; b) intermediate consumption and value added; and c) resources and impacts. Considering z seasons, the expression to explain the production for each season considering full information would be as follows:

$$F_{zf} = \hat{f}_z (I - A_z)^{-1} \hat{y}_z = \hat{f}_z L_z \hat{y}_z = P_z \hat{y}_z \qquad (2)$$

Expression (2) is a seasonal extension of expression (1), where matrix result F_{zf} provides environmental factor f embodied in production by the world economy in season z with full information. The required information in expression (2) is not available; thus, there is no previous literature that builds MRIO models from a seasonal perspective. An interesting initial approach analyses the quarterly impact of production in Brazil[38], using estimated input-output tables with quarterly national accounting data. However, this approach is not developed in a MRIO framework and for an environmental implementation. In any case, in a context of increasingly available microdata and MRIO time series, in which possibilities for IO models are also further developing[39], and of increasing computing capabilities (plus the extension of updating/regionalization methods), we foresee in a not distant future the ability to accomplish explain the full “seasonal MRIO model” presented in the Supplementary Information (SI from now onwards). One important objective of this article is to open minds and experiences to the attempt of doing such a full temporalization.

Our proposal for the empirical section is to build a partial-information seasonal MRIO model, allowing for seasonal variation in the final demand. The expression for this MRIO model with seasonal variation in the final demand or partial information is as follows:

$$F_z = \hat{f}(I - A)^{-1}\hat{y}_z = \hat{f}L\hat{y}_z = P\hat{y}_z \qquad (3)$$

where the resulting matrix F_z provides the environmental factor, f embodied in production by the world economy caused by seasonal variation in final demand in season z. The seasonal variation in the final demand captures the different monthly mix of countries of origin of agricultural imported products (for example, a larger presence of South American countries in winter and a higher proportion of European countries in summer); however, the annual model would only consider the average annual proportions. Indeed, the sum of domestic and imported final demand for fruits and vegetables for all seasons is equal to their final domestic and imported annual demand. Furthermore, in comparison with the ideal full-information seasonal model, the partial-data implementation we do have has the interesting feature of isolating that "country effect" from the impact of the other two missing changes (change in the production structure, A, and change in the emission intensity, f).

Our MRIO with seasonal final demand model continues to consider, as any MRIO model implicitly does, that production and emission coefficients (A and f, respectively) are similar for all products within a group and months as an annual average. However, our model explains changes in consumption, imports and export patterns for agricultural products by month (both the countries of origin of imports and the countries of exports destination are different), while the conventional MRIO does not allow one to consider this variability throughout the year. In this case, similar to the argument that the disaggregation of IO data, even if based on few real data points, is superior to aggregating environmental data in determining input-output multipliers[40], we find that temporalization (disaggregation in time) of the final demand data, even if not accompanied by other changes in the structures, provides interesting and (we consider) more realistic results for the environmental metrics associated with the agri-food sectors. (Refer to section S1.5 in the SI where we analyze the changes in the resulting monthly coefficient in relation to the annual average from changes in the country mix.)

II.2. Seasonal avoided footprint by imports (SAFM)

Building on the concepts of the balance of embodied emissions[32, 41-46] and the balance of avoided emissions[19-25], we define the seasonal avoided footprint by imports (SAFM) as the difference between embodied emissions in fruits and vegetables from imports for region ***r*** by unit of time (month of season) minus domestic avoided emissions (emissions required to domestically produce and substitute those imports). The idea behind the SAFM can be extrapolated to any factor content: emissions, water, materials, and energy. The formula for this $SAFM_{iz}^{r}$ for region ***r*** due to its trade with region s in the month or season z of agriculture product–i is shown by equation (4) and for all the fruits and vegetables by equation (5):

$$SAFM_{iz}^{r} = \hat{f}[I - A]^{-1}\hat{y}_{iz}^{sr} - \hat{f}[I - A]^{-1}\hat{y}_{iz}^{*sr} \qquad (4)$$

$$SAFM_{z}^{r} = \begin{pmatrix} f_i^r & 0 & 0 & 0 \\ 0 & f_j^r & 0 & 0 \\ 0 & 0 & f_i^s & 0 \\ 0 & 0 & 0 & f_j^s \end{pmatrix} \begin{pmatrix} L_{ii}^{rr} & L_{ij}^{rr} & L_{ii}^{rs} & L_{ij}^{rs} \\ L_{ji}^{rr} & L_{jj}^{rr} & L_{ji}^{rs} & L_{jj}^{rs} \\ L_{ii}^{sr} & L_{ij}^{sr} & L_{ii}^{ss} & L_{ij}^{ss} \\ L_{ji}^{sr} & L_{jj}^{sr} & L_{ji}^{ss} & L_{jj}^{ss} \end{pmatrix} \left[\begin{pmatrix} 0 & 0 \\ 0 & 0 \\ y_{iz}^{sr} & 0 \\ 0 & y_{jz}^{sr} \end{pmatrix} - \begin{pmatrix} y_{iz}^{sr} & 0 \\ 0 & y_{jz}^{sr} \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \right] (5)$$

While $\boldsymbol{\hat{y}_{iz}^{sr}}$ are exports from s to r (or imports by r from s), the vector $\boldsymbol{\hat{y}_{iz}^{*sr}}$ is defined as a diagonalized vector of avoided imports in season z; it includes the imported agricultural products that can be substituted by in-season domestic products. A positive sign of SAFM will indicate that imported fruits and vegetables generate more emissions or water use than do the domestic in-season produce and that therefore trade is environmentally harmful. In that case, a better result could be obtained by substituting imported fruits and vegetables by domestic production, which would be more environmentally efficient. Otherwise, a negative sign of SAFM will imply that importing those products is better for the environment as the emissions embodied are lower than those that would result from producing domestically. A change in diet from consuming local in-season goods in the analyzed region would increase emissions or resource use since imported products are more environmentally efficient or use fewer resources.

Regarding the substitution of imports by domestic production, there are three possible options: prices, kg or calories. Our proposal, in substitution in value terms, is respectful of budget restrictions, ensuring that final consumers would spend the same amount of money on domestic fruits and vegetables as they currently do on imported products. Therefore, substitution is economically viable for households, since total expenditure is fixed. The three options have both advantages and disadvantages; those aspects are fully discussed in S.5 in the SI.

II.3. Materials.

Despite the growing number of global multiregional input-output databases that provide annual data for the different countries/regions, there are no monthly or seasonal data. Therefore, we have built our "temporalization of the MRIO" combining information from different sources. We have used EXIOBASE version 2.2. for 2007[47-50], which provides data for an extended environmentally multi-regional input-output (EE-MRIO) model for 163 industries and 48 countries and regions. CO_2e emissions are defined using the Global Warming Potential 100, defined so kg CO_2e = 1x kg CO_2 + 25 x kg CH_4 + 298 x kg N_2O + 22800 x kg SF_6, as characterized in the EXIOBASE v2.2.2. For the satellite accounts of water, we utilize the data both on the blue water (ground and surface water) and green water (from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants). In addition, to not simply examine the blue water consumption or uses but to also particularly focus on the effects for "scarce water" (increasing arguments in favor of placing the focus more on this aspect are appearing in the literature, in a context of increasing demands, vulnerabilities derived from climate change, etc.), we apply to the blue water the ratio of the freshwater withdrawal to the total renewable water resources[51, 52], obtaining "scarce blue water" volumes. For all the countries, we preferably used this information for the period 2008-2012; otherwise, the periods 2003-2007 and 2013-2017 (average if existing in both) were used; and in exceptional cases, the period 1998-2002 was used. The ratio of "scarce water" for the rest of the world regions was obtained at country level; with it, a weighted (by the total renewable water resources) "scarce water" ratio was obtained for the 5 regions (WA, WE, WF, WL, WM, see SI). Using the Spanish

Ministry of Agriculture data and different references for calendars of fruits and vegetables for the different fruits and vegetables, we have classified the months of harvest and best consumption in Spain (see the "Specification and calendar" in the SI). In-season fruits and vegetables in a particular month are those that can be produced in Spain in that month (for example, watermelon from May to September), while out-of-season fruits and vegetables are not generally produced in that month (watermelon from October to April). Data for traded (imported/exported) agricultural products are provided by the Spanish Customs Office for 2011[53] with details on weight, value, country of origin/destination and mode of transportation. Scheme 1 summarizes the procedure for calculation and interpretation.

Scheme 1. Calculation and interpretation of results from SAFM

Note: SAFM = Emissions or water embodied in imported fruits and vegetables from region r in a particular month minus emissions or water avoided by imports. If SAFM <0, emissions embodied in imports are lower than the emissions required to domestically produce and substitute those imported fruits and vegetables.

III. MAIN RESULTS

The production capacity of Spain in fruits and vegetables both for domestic consumption and for foreign demand is remarkable[54], resulting in its ability to implement measures of import substitution by domestic production depending on the country of origin and the environmental pressures resulting from the imported products (see section SI2 of the supporting information for a detailed analysis of Spanish trade of fruits and vegetables). Our results show a positive sign in the annual Spanish seasonal avoided footprint by imports (SAFM) for both fruits and vegetables in 2011, except for scarce blue water for out-of-season fruits (Tables 1 and 2), revealing a general increase in CO_2e and water footprints because of fruit and vegetable imports. Due to the higher efficiency of domestic production in terms of both CO_2e and water use for these products, Spanish final consumers could reduce annual carbon emissions and water use in important quantities if the imports of fruits and vegetables are replaced by domestic production.

1. Fruits seasonal avoided emissions by imports (SAFM).

Focusing on fruits, the annual results support the idea of a highest efficiency in natural resources use for the four metrics used (except for one category, see Table 1). The substitution of imports by domestic production would have saved 317 tCO_2e emissions to the atmosphere (33% in relative terms to the total emissions embodied in imports in 2011), 1.6 km^3 of blue and green water (72%), 0.3 km^3 of blue water (45%), while the reduction in scarce blue water will be minimal (1 Mm3, 1%). The results are now analyzed conditional to seasonality: Substituting imports by domestic production for fruit seasonal consumption would have saved the environment 79.29 tCO_2e (24%) and 0.5 km^3 (65%), 0.07 km^3 (35%) and 0.002 km^3 (5%) of green and blue, blue and scarce blue water, respectively. The results are similar for out-of-season fruits, with potential reductions for tCO_2e, total green and blue water, and blue water of 39%, 75%, 50%, respectively, while trade actually reduces the content of scarce blue water by

2%. These impressive figures are due to the much higher embodied emissions for fruits originating from a certain dataset of aggregated regions such as the Rest of Africa, Rest of America and Asia and Pacific (see Table S7 in the SI), together with the high weight of those imports, particularly for the Rest of America. Some of these countries have coefficients for embodied CO_2e and water from 3.2 to 9.2 times those of the Spanish ones. For blue water, which is linked to water management and water alternative uses other than agriculture, potential reductions are small and close to zero in absolute values, and even slightly negative for out-of-season fruits. However, strong reductions are possible for specific regions; that is, the blue scarce water intensity embodied in fruits imported from Africa is 9.2 times the Spanish value. The aggregated nature of the main actors, the Rest of Africa, America and Asia warrants a cautious interpretation of the results[55].

The SAFM analysis by month for both types of fruit allows further insight of these results. The analysis reinforces the conclusion of a higher efficiency for Spanish production of fruits that holds during the year for all footprints with the exception of scarce water, for which the saving potential follows a seasonal pattern. Spanish production is more efficient than importing from the countries of origin; this is particularly the case for out-of-season fruits. This finding allows approximately 2 to 3 times higher savings, as an annual mean, if trade were to be more highly regulated for CO_2e, blue and green and blue water. However, there is no clear pattern for blue scarce water. There is a potential reduction in blue scarce water consumption by substituting imports with domestic production for in-season fruits; however, the reduction is small. Therefore, scarce blue water consumption would be the main shortcoming of the fruit production processes. Imported fruits have less embodied water in various months: 6 for in-season fruits and 9 for out-of-season ones. Country of origin is, to a large extent, the main factor behind these differences; that is, the results show that scarce blue water savings are mainly due to the France, Rest of Latin America, Italy, Portugal, the Netherlands and the United Kingdom in-season fruit imports, as shown on the left side of Figure 1. In contrast, imports from the Rest of Africa, Asia, and Rest of Middle East imply increases in scarce blue water, as shown on the right side of Figure 1. For out-of-season fruits, savings in scarce blue water are generated by imports originating mainly from the Rest of Latin America, France, Brazil, Italy and the Netherlands; however, the increases in scarce blue water are concentrated, more than 90%, in imports from the Rest of Africa (Figure S8 of the SI). Although the quantities are small in absolute/annual terms because the different sign effects of different countries balance out, the changes are marked in relative terms, given that scarce water efficiency is higher in most countries of origin. The large quantity of fruits that are produced in semi-desert areas in Spain explain these results.

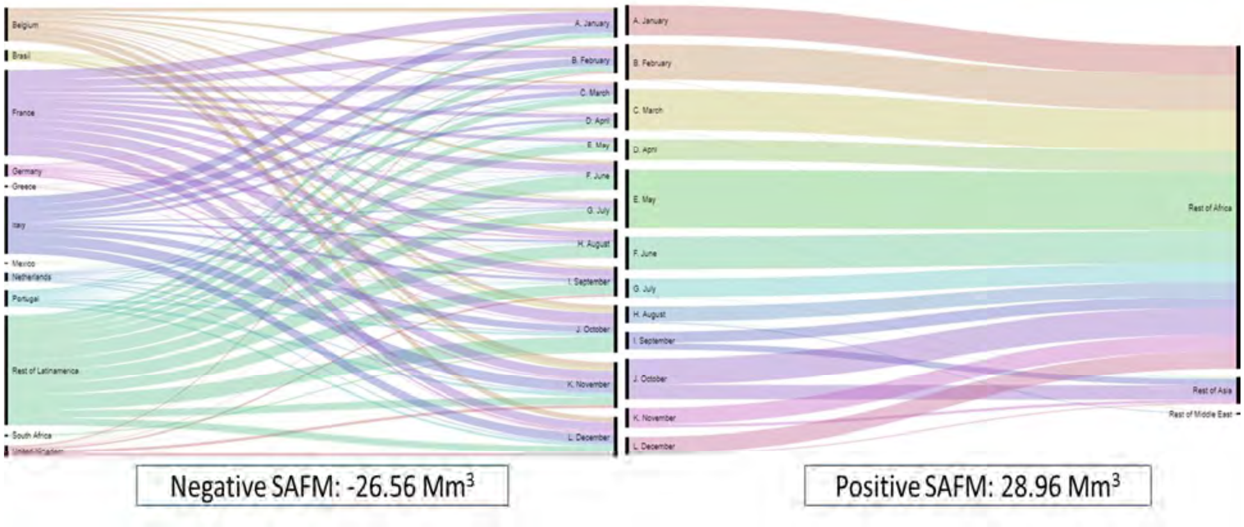

Figure 1. SAFM of scarce blue water for in-season fruits (main countries), 2011.

Note: SAFM = Emissions or water embodied in imported fruits and vegetables from region r in a particular month minus emissions avoided by imports. If SAFM <0, emissions embodied in imports are lower than the emissions required to domestically produce and substitute those imported fruits and vegetables.

Moreover, our results show a degree of substitutability among hydrological resources and carbon emissions for both types of fruits. Accordingly, months where imports imply a high increase in carbon emissions (i.e., 46% for out-of-season in December) accompany a reduction in scarce blue water (-2%). Therefore, the reduction (increase) in GHG impacts imply an increase (reduction) in water depletion (see comment on Figure S4 in section S3 of SI for detailed analysis).

Table 1. Fruits' monthly seasonal avoided CO_2e emissions and water by imports, SAFM (In-Season and Out-of-Season, also with respect to the metric embodied in imports, EM) for 2011, kt for CO_2e and Mm^3 for water uses.

In-season Fruits								
	CO_2e Emissions		Green and Blue		Blue		Scarce Blue	
	SAFM (kt)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)
January	3.59	15%	21.6	51%	0.45	4%	0.2	6%
February	3.39	14%	29.1	60%	2.8	21%	0.9	22%
March	3.64	18%	35.4	68%	5.3	38%	1.7	38%
April	2.50	18%	23.1	67%	3.5	37%	0.6	24%
May	3.72	22%	54.4	81%	10.4	61%	3.7	63%
June	6.93	26%	45.5	70%	7.7	44%	0.5	14%
July	5.70	27%	37.5	71%	6.2	44%	-0.1	-5%
August	6.92	26%	40.6	68%	6.1	38%	-0.8	-35%
September	7.55	26%	40.6	66%	8.2	43%	-0.8	-29%
October	18.26	33%	83.7	70%	17.2	48%	-0.2	-4%
November	10.84	25%	39.7	56%	2.8	15%	-1.9	-56%
December	6.25	19%	20.2	44%	0.0	0%	-1.5	-52%
Annual	79.29	24%	471.5	65%	70.6	35%	2.4	5%
Out-of-Season Fruits								
	CO_2e Emissions		Green and Blue		Blue		Scarce Blue	
	SAFM (kt)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)
January	15.63	43%	75.9	79%	10.8	51%	-0.6	-20%
February	19.42	41%	87.1	76%	10.1	41%	-2.1	-84%
March	19.02	32%	89.84	70%	10.7	35%	-1.5	-29%
April	23.24	31%	160.2	76%	25.5	50%	5.9	41%
May	28.69	35%	142.8	73%	31.8	54%	-0.4	-5%

June	21.09	36%	95.1	72%	20.0	51%	-0.6	-10%
July	13.29	36%	71.2	76%	15.0	56%	0.9	18%
August	25.11	43%	92.0	74%	21.4	56%	-1.2	-29%
September	21.97	43%	75.8	73%	15.2	51%	-1.5	-44%
October	12.44	43%	42.4	72%	6.3	43%	-0.3	-13%
November	16.25	51%	80.1	84%	10.7	58%	0.1	5%
December	21.47	46%	110.1	82%	15.2	54%	-0.1	-2%
Annual	237.63	39%	1122.6	75%	192.7	50%	-1.5	-2.4%

Note: A positive sign for the seasonal balance of avoided footprint (SAFM) indicates that the Spanish fruit trade with other regions increases global emissions, as the emissions from the imports are higher than the emissions that would be generated if it produced its imports. Spain would then produce fruits that incorporate a lower virtual (carbon/water) footprint than that of the imported, more intensive (carbon/water) goods. The substitution of imports by domestic production would imply global savings with respect to a baseline (the current trade patterns). A negative sign indicates that Spanish trade avoids emissions/water, as that country imports goods with a lower carbon/water embodied, which replaces higher polluting domestic production. The SAFM is obtained in absolute quantities but also as a proportion of the metric in question, which is embodied in imports (EM).

Key: 3.59 kt of CO_2e emissions of Spain for in-season fruits in January show how much greater emissions are from its imports than the emissions that would be generated if it produced its imports. This difference represents 15% of the CO_2e emissions embodied in imports in that month for these products.

Source: Own elaboration from the modeling exercise, departing from the data of EXIOBASE and trade data.

2. Vegetables seasonal avoided emissions by imports (SAFM).

Seasonal patterns are better defined for vegetables than they are for fruits. The results again show a higher efficiency for Spanish production than that of its imports as an annual average for all the analyzed footprints for in-season vegetables and two out of four for out-of-season; however, the exceptions are numerous at the monthly level. All year long, domestic vegetable consumption would have reduced emissions to the atmosphere by 53.66 tCO_2e (11% in relative terms) and water use by 0.84 km^3 of blue and green water (67%), by 0.10 km^3 of blue water (31%) and by 0.06 km^3 of scarce blue water (48%). Although the blue and scarce blue water use change sign during the year, the potential savings if imports were avoided would overcompensated those periods were Spanish efficiency lags those countries that produce its substitutes. For vegetables, the out-of-season type shows more moderate potential reductions and even negative results for blue and scarce blue water, such that total results are mainly led by seasonal vegetable consumption patterns, contrary to the fruits case. Conversely, there are certain marked similarities with fruits; again as scarce blue water, the footprint that would clearly worsen if Spanish imports were suppressed.

Monthly results for vegetables SAFM are shown in Table 2. Focusing on in-season vegetables, the results show that international vegetable trade entails a reduction of water used for blue and scarce blue water for the summer period; however, for any other month for these two impacts and all year long for carbon emissions and green and blue water, all measured environmental impacts increase due to imports. Potential savings due to imported substitution by domestic production are explained for the water case for those imports originating from African countries, which, as previously noted, have an intensity of scarce blue water that is nearly ten times that of the Spanish. For out-of-season vegetables, imports allow saving on scarce blue water in every month but July, with a peak value in March of 389%. In addition, green and blue water savings appear between February and May, and CO_2e and blue water savings due to imports appear from January until May. Since, for most cases, vegetables production requires larger quantities of water than fruits, savings are remarkable whenever imported out-of-season vegetables originate from a region where production is in-season. As an example, more detailed analysis for in-season vegetables shows how savings in scarce blue water related to imports are important for the Rest of Latin America, France, Italy, Belgium and Portugal (left side in Figure 2). In contrast, imports from the Rest of Africa, Rest of Asia and Rest of Middle East generate important increases in the use of scarce blue water (right side in Figure 2). For out-of-season vegetables, although variations are less positive or more negative than for fruits, savings or increases of scarce water originate from the above cited regions; however, savings are mainly concentrated in France and the Rest of Latin America, with the increases in imports from the Rest of Africa (Figure S9.of the SI).

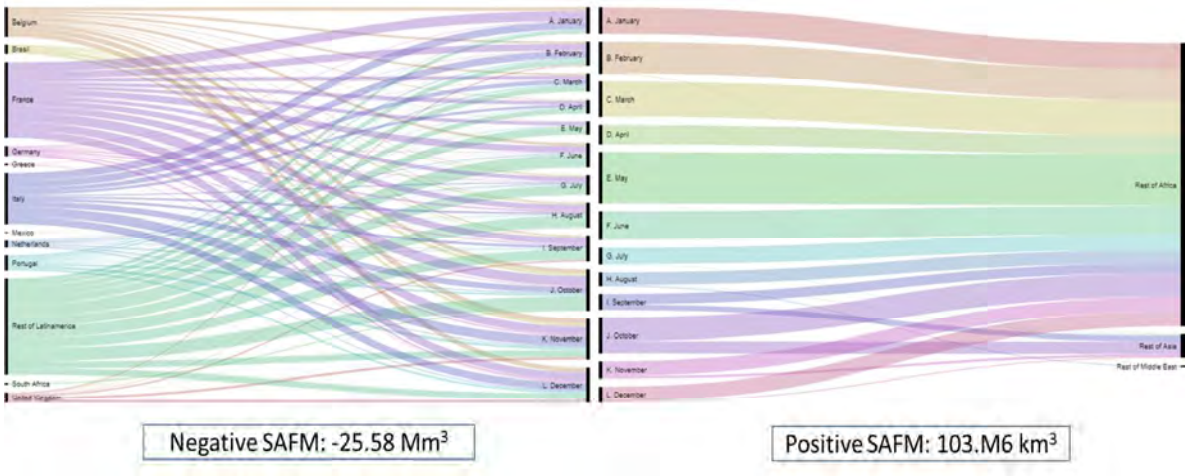

Figure 2. SAFM of scarce blue water for in-season vegetables (main countries), 2011.

Note: SAFM = Emissions or water embodied in imported fruits and vegetables from region r in a particular month – emissions avoided by imports. If SAFM <0, emissions or water embodied in imports are lower than the emissions or water required to domestically produce and substitute those imported fruits and vegetables.

For CO_2e, colder months require the use of greenhouses, with an undesirable effect on carbon emissions. This case did not apply for fruits since their production within greenhouses is much less common. The relative figures for avoided impacts are very impressive, particularly for blue ,and even more scarce blue, water in winter, and lead to a negative annual mean for vegetable overall, although the absolute figures are small. Moreover, our results show a clear complementarity relationship among hydrological resources and carbon emissions for both types of vegetables. These results provide environmental arguments that justify the idea of substituting domestically produced greens by imported ones for certain products and months, in-season in summer and out-of-season in winter, while imported ones should be substituted by domestically produced any other month (see comment to Figure S4 in section S3 of SI for a detailed analysis).

Table 2. Vegetable monthly seasonal balances of avoided CO$_2$e emissions and water (In-Season and Out-of-Season, also with respect to the metric embodied in imports, EM) for 2011, kt for CO$_2$e and Mm^3 for water.

In-Season Vegetables								
	CO$_2$e Emissions		Green and Blue		Blue		Scarce Blue	
	SAFM (kt)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)
January	4.23	13%	114.2	80%	18.7	56%	11.3	70%
February	4.87	14%	116.4	80%	19.3	56%	11.4	70%
March	11.47	23%	141.9	79%	24.3	55%	14.9	70%
April	5.63	16%	106.1	78%	16.9	53%	11.3	70%
May	4.99	16%	88.2	77%	13.6	50%	9.1	67%
June	2.04	11%	34.8	69%	4.1	33%	3.0	53%
July	0.02	0%	2.4	19%	-2.0	-60%	-0.5	-43%
August	0.34	3%	-0.9	-9%	-3.0	-109%	-1.1	-123%
September	0.57	4%	1.6	11%	-2.5	-55%	-0.9	-71%
October	1.07	6%	22.9	57%	1.5	15%	1.6	36%
November	1.46	6%	78.6	78%	11.9	52%	8.7	71%
December	2.52	8%	86.2	76%	12.1	47%	9.2	67%
Annual	39.20	13%	792.3	75%	114.8	45%	78.0	63%
Out-of-Season Vegetables								
	CO$_2$ Emissions		Green and Blue		Blue		Scarce Blue	
	SAFM (kt)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)	SAFM (Mm^3)	SAFM/EM (%)
January	-0.56	-3%	2.3	11%	-3.8	-63%	-2.4	-263%
February	-1.47	-8%	-3.0	-19%	-5.3	-118%	-2.4	-302%
March	-1.30	-7%	-4.1	-28%	-5.5	-136%	-2.5	-389%
April	-0.67	-5%	-6.4	-73%	-5.0	-176%	-1.8	-231%
May	0.43	3%	-2.3	-23%	-3.3	-110%	-1.1	-118%
June	2.27	21%	1.6	16%	-0.9	-26%	-0.7	-102%
July	3.66	26%	14.1	58%	1.5	22%	0.3	17%
August	3.65	23%	9.7	45%	-0.0	0%	-0.5	-33%
September	2.46	20%	11.8	54%	1.3	21%	-0.3	-24%
October	2.75	29%	8.2	56%	1.1	24%	-0.5	-84%
November	1.80	22%	8.3	57%	1.0	23%	-0.5	-98%
December	1.45	14%	8.9	50%	0.6	11%	-0.9	-151%
Annual	14.46	9%	49.0	25%	-18.5	-32%	-13.4	-117%

Note: A positive sign for the seasonal avoided footprint by imports (SAFM) indicates that Spanish vegetables trade with other regions increases global footprint, as the emissions or water from its imports are higher than the emissions or water that would be generated if it produced its imports. Spain then would produce vegetables that incorporate a lower virtual (carbon/water) footprint than that of the imported, more intensive (carbon/water) goods. A negative sign indicates that Spanish trade avoids emissions/water, as that country imports goods with lower carbon/water embodied, which replaces a more polluting domestic production.

Key: 4.23 kt of CO_2e emissions of Spain of in-season vegetables in January, show how bigger are emissions from its imports than the emissions that would be generated if it produced its imports. This difference represents 12% of the CO_2e emissions embodied in imports in that month for these products.

Source: Own elaboration from the modeling exercise, departing from the data of EXIOBASE and trade data.

3. Fruits and vegetables SAFM by country of origin of imports.

Disregarding the seasonal patterns, we focus now on annual impacts of the origin of products. It is possible to identify the Rest of Africa as the main responsible region for a higher quantity of scarce water impacts and America (mainly South America, see S4 in SI) as the main responsible region for CO_2e impact (see Figure S6 of supporting information). The results show that the Rest of Latin America imports imply an important increase in CO_2e emissions together with a reduction in scarce water use, which is consistent with the discussed idea of substitutability between water and energy. Belgium shows a similar pattern with moderate figures. The main fruit import providers for Spain are Brazil (mainly melons, watermelons and pineapple) with high linked carbon emissions, Costa Rica (mainly pineapple and banana), which is included in the Rest of Latin America and Peru. Additionally, for scarce blue water, SAFM show potential savings with very low values among most countries, with the Rest of Africa as a notable outsider. In contrast, there are no major CO_2e emitters; emissions embodied in imports are homogeneously distributed.

The country of origin analysis of annual in-season vegetables SAFM leads to the conclusion that negative impacts on scarce blue water are mainly due to African imports, which represent over 90% of the total (see Figure S7 of supporting information). In contrast, European and the Rest of Latin America-originated purchases allow water savings compared to that of Spanish production. The graph shows the important weight of water savings for products originating from France (potatoes and cabbage), Portugal (tomatoes in October-November), South American countries (mainly onions, shallots, garlic and leeks), Italy (artichoke, tomato), Belgium (due to its re-export market strategy for potatoes and lettuce), and the Netherlands (with a profile similar to the Netherlands for onions, potatoes, cabbage, cucumber and pepper and tomatoes, citrus fruits, apples and pears). For approximately every country, both water use savings and increments are higher for in-season than for out-of-season vegetables, mainly because out-of-season imports are smaller in quantity. Green and blue water consumption would also be smaller if imported vegetables were substituted by domestic production, mainly for those originating from the Rest of Africa (with embodied water coefficients 9.2 times those of the domestic ones). The substitution of these Rest of Africa imports would be reduced by 0.8 km^3, virtually the whole impact, and its effect would basically occur from November to May.

The SAFM concentration for vegetables is also high for CO_2e but at a lower level. Among the countries that are the origin of Spanish vegetable imports with a negative environmental impact, we find BE (mainly potatoes and leeks), the Rest of Latin America (onions, asparagus and garlics), the Middle East (artichokes from Egypt and early potatoes from Israel) and the Rest of Africa (mainly beans but also tomatoes and peppers) and China (mainly garlics). Imports in terms of kilograms from France (mainly potatoes, and beans and carrots) or Portugal (mainly tomatoes, followed by potatoes and leeks) are much more important; however, those imports are more efficient both in terms of CO_2e and water usage. France and Portugal allow the reduction of emissions for both water and carbon. The Rest of Africa and Rest of Middle East import results show an increase in both types of impacts. An exception is Belgium and a small number of countries whose imports reduce the Spanish water impact but increase CO_2e emissions.

In the following four maps, we illustrate visually the SAFM of CO_2e and scarce blue water, which quantifies reductions (if negative) or increases (if positive) in these variables when comparing current trade patterns to domestic production technology (i.e., if the imports were produced in Spain itself). The analysis then is done for Spain, in reference to the trade partner countries and regions. In the months selected, which generally are very representative of the directions of the yearly changes per country, both the positive or negative variations of scarce blue water and carbon emissions are very relevant. In the case of the two maps (Figure 3) of in-season fruits in October, we find many regional differences for blue water and CO_2e emissions, highlighting a kind of trade-off for the two variables in the savings with respect to many of those origins. For example, with Brazil, one may observe the negative balance in scarce blue water (savings with current trade patterns) and very positive in CO_2e (increases with current trade patterns). This result also occurs with Italy, similar to that in Portugal and other European countries with whom Spain mainly trades, having a negative balance in the blue water (global savings with current trade patterns) and a positive balance in CO_2e. The results for this month, October, for South Africa are also very interesting, because they provide a more marked negative balance for scarce water (savings with current trade patterns) and a more markedly positive balance for CO_2e. These two maps of in-season fruits for October clearly illustrate the described concept of a “positive hotspot” of France, with avoided blue water and CO_2e emissions with current trade patterns; this finding is in contrast to China, the Rest of Asia and the Rest of Latin America.

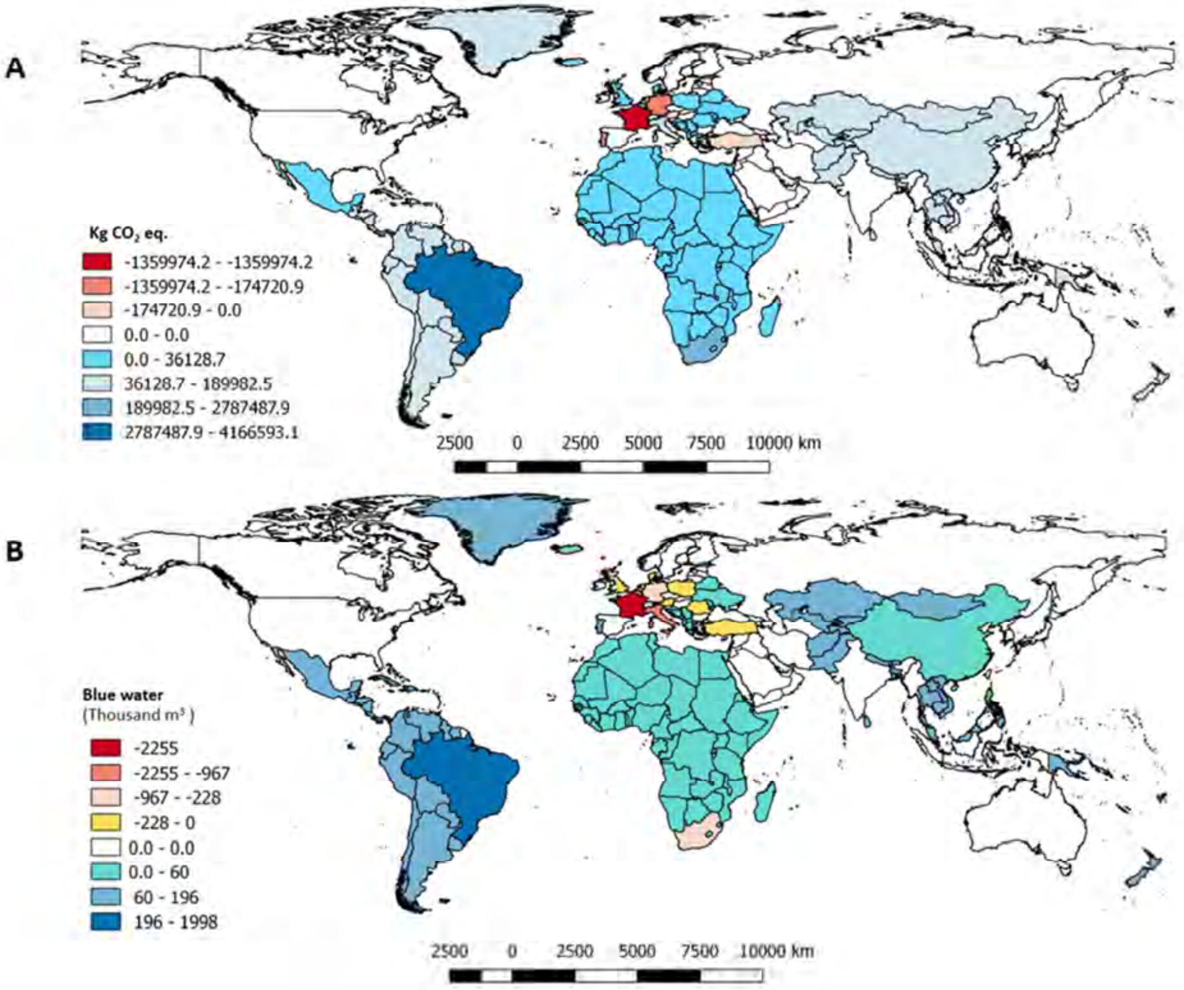

Figure 3. SAFM of in-season fruits in October for CO_2e (kg) emissions (A) and blue water (1000 m^3) (B), 2011

Source: Own elaboration from the modeling exercise, departing from the data of EXIOBASE and trade data. QGIS software (www.qgis.org).

Note: The analysis follows the same regional classification as in all the article, i.e., the 2nd column of Table S3, "Name (Regions in all other figures)". Hence, all countries within a region show the same color.

In the case of the two maps (Figure 4) of scarce blue water for out-of-season vegetables, we may observe how the differences across months for the same variable are less marked than the differences among variables. In this regard, the cited important (global) avoidance of scarce blue water with the imports from France is maintained, and the same applies for the increase in (global) scarce blue water with the current imports from Rest of Africa and Middle East. In any case, we may continue to observe certain key differences between March and August. In March, the United Kingdom and Brazil show more negative balances (negative SAFM, which imply savings with current trade patterns), and the the Rest of Africa shows more positive balances.

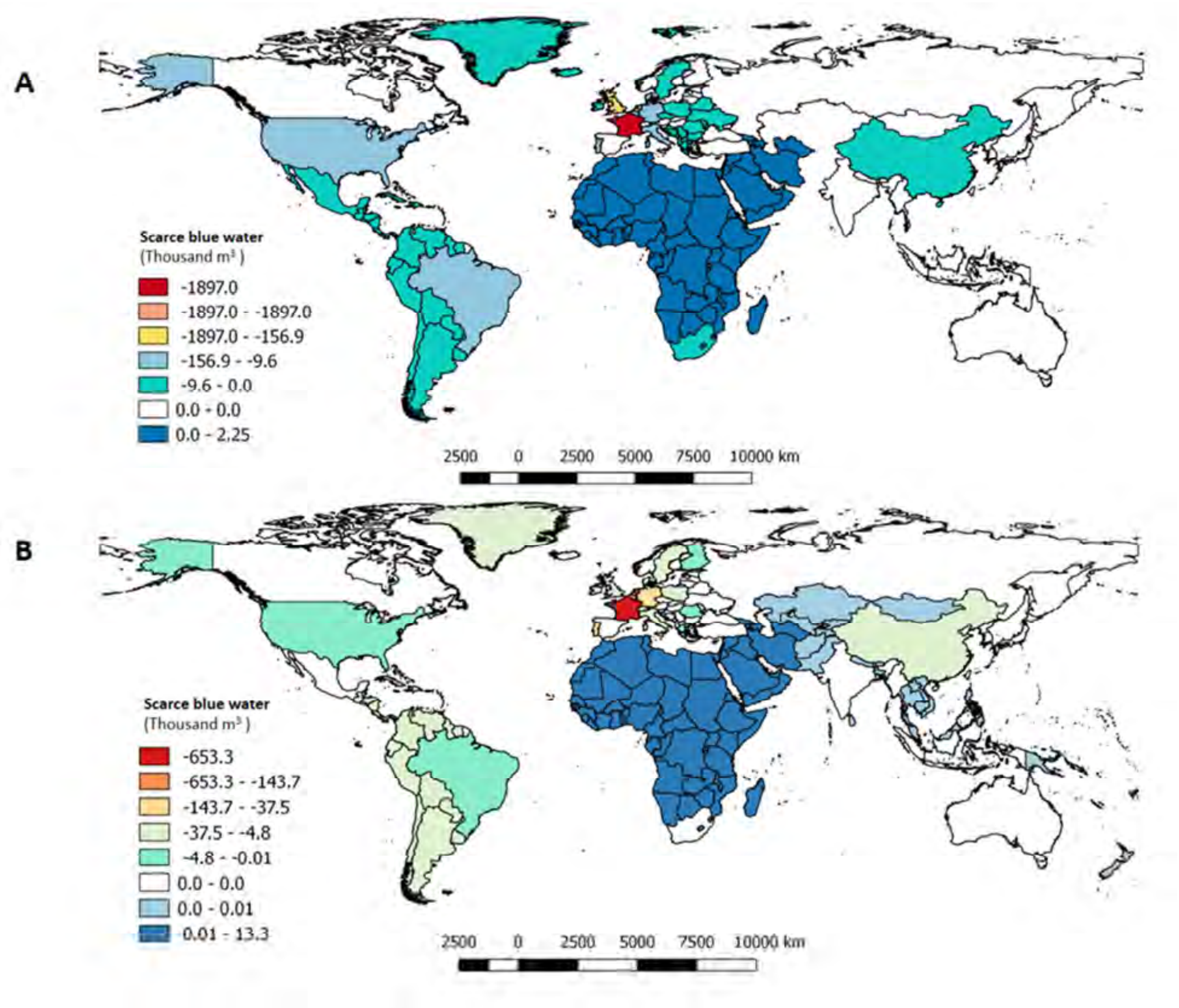

Figure 4. SAFM of scarce blue water (1000 m^3) for out-of-season vegetables March (A) and August (B), 2011

Source: Own elaboration from the modeling exercise, departing from the data of EXIOBASE and trade data. QGIS software (www.qgis.org).

Note: See note in Figure 1.

IV. DISCUSSION IN TERMS OF ENVIRONMENTAL POLICIES

The development of a MRIO with a **seasonal** final demand model has allowed us to show that timing by month is a key factor to evaluate the potential environmental impact of local and seasonal consumption when substituting fruits and vegetables imports for domestic production. The proposed substitution implies that consumers are open to replace products, i.e., imported pineapples by domestic oranges, instead of considering an immutable consumption pattern for households.

Although, in 2011, the Spanish economy had an environmentally efficient agricultural sector, local and seasonal consumption does not always imply a lower carbon and water footprint. In particular, importing from France contributes to reduce both CO_2e and scarce blue water, while the opposite is true for imports from Africa. For imported fruits and vegetables from Latin America, a trade-off appears as they require less water but have a greater CO_2e content (see section S4 in the SI).

Once local and seasonal consumption of fruits and vegetables is temporalized, we find that for a significant number of months, domestic consumption would have a greater environmental impact in terms of water and CO_2e emissions. The savings from international trade are more pronounced for out-of-season fruits, due to a more scarce water intensity in domestic production than that in imported alternatives, and for out-of-season vegetables, due to higher domestic intensity not only in scarce water but also in blue water and CO_2e. The highest savings by trade are shown for out-of-season vegetables; they range from 15% of CO_2e in April to 389% of scarce water in March. Instead, domestic production substitution leads to CO_2e, green and blue water reductions in all the months for all fruits and most months for in-season vegetables, ranging the highest savings from 23% of CO_2e in February to 80% of green and blue water in January and February, both for in-season vegetables.

Focusing on the water results, which have been shown to be more significant in terms of potential to reduction, 25% (close to 5.5 km^3) of all the blue water consumed in Spain is directly used for fruits and vegetables. Regarding the consumption side, we estimate that the consumption of fruits and vegetables represents approximately 11% of the total water footprint in Spain and close to 20% of the water footprint related to food sectors. Within this context and focusing on scarce water as sensitive resource to over-exploitation, the results show that regional differences matter. Trade with Africa and Asia leads to water stress; therefore, it should be reduced. However, imports from Latin-American and Europe lead to a reduction in water use when compared to that of Spanish production. Analyzed by product, it is always in-season imports, for fruits and most months for vegetables, that require more water; the highest water requirement due to imports occurs in May for fruits, 63%, and from November to May for vegetables, ranging from 67% to 71%. In terms of products and origins, this finding is particularly true for fruits from Africa (banana, strawberry, oranges). Imported products that save water are apples from France and banana from Ecuador for in-season fruits; pineapple form Costa Rica and melon from Brazil for out-of-season fruits; and potatoes from France for vegetables. Top driving products by origin can be found in Tables S6 and S7 in the SI.

We have observed that when combined, the substitution of imports by having domestic production of fruits and vegetables would have saved globally 2.44 km^3 of green and blue water, 0.4 km^3 of blue water and 0.06 km^3 of scarce blue water. Therefore, producing imported fruits and vegetables domestically would imply moving from needing 5.4 km^3 of blue water to 6.0 km^3, i.e., needing additional 0.5 km^3 while simultaneously globally avoiding 0.9 km^3 of blue water. This increase obviously could generate additional water challenges in Spain, e.g., increases of scarce water (around 10%). Another means to consider the maximum potential of water saving would be to substitute those imports with higher embodied water intensities than Spain, e.g., producing domestically current large imports of fruits and vegetables from a few regions with very high-water intensities (the Rest of Africa, Rest of Asia, Middle East, and India). This result could lead to saving globally 0.5 km^3 of blue water (increasing blue water in Spain by 0.2 km^3 for producing them but avoiding 0.7 km^3). This is particularly the case for banana from Ecuador, avocado from Peru, pineapple from Costa Rica and melon from Brazil (see Table S6 in SI). Obviously, these type of changes call for additional investigation, particularly on the climatic conditions that make those productions possible and on the dietary/nutritional characteristics of the substitution; in any case, this study calls for additional focus on the possibilities of these type of substitutions.

Calling for domestic fruit and vegetable consumption is not an adequate all-year-around option. The examination of the time patterns shows that, for vegetables, local and seasonal consumption should be avoided in July, August and September for in-season vegetables, since imports save water, while the emissions are increased by only 0 to 4%. For out-of-season vegetables between January and May, we find savings in emissions, blue and scarce blue water due to imports, a total of 3.6 kt of CO_2e, 23.0 Mm^3 and 10.2 Mm^3 respectively for the 5 months, a mean reduction of 4% for CO_2e, 112% for blue water and 250% for scarce blue water. Regarding fruits, potential import substitution savings are much more isolated and less significant. In addition, in relation to fruits, there is a monthly substitution between the blue water and carbon footprint that makes it impossible to clearly identify the months for which the substitution is more appropriate; it is not easy to prioritize one footprint over the other. We can only say that the fact that relative changes in trade impacts of any sign are higher (in %) in CO_2e emissions than those in blue water reveals that carbon is more sensitive than water when it comes to changes in food supply origin.

Although the seasonal adjustment is not present, a comparison with the input-output previous literature that focuses on the effect of diet changes on carbon emissions shows a modest impact on emissions explained by the low weight of these kind of products on the diet[56]. Tukker et al.[57] find a potential reduction of 9% in CO_2e emissions when switching to a vegetarian diet, while the results of Pairotti et al.[58] and Cazcarro et al.[59] show a potential reduction of 12.7% for CO_2e and 9% for the water footprint, respectively, for switching to a more healthy diet. The results found in this paper are more substantial in terms of CO_2e, blue water and, particularly, scarce water, for out-of-season fruits and vegetables. These differences lead us to the conclusion that less significant results in previous studies were due to yearly averages that hide fluctuating changes, with a remarkable potential in curbing emissions and resource overuse goals when temporalization is considered. However, although potential reductions on environmental impacts are found, more meaningful results would be achieved if this measure was combined with a reduction in meat consumption and in overconsumption[60, 61].

We have identified the months in which the substitution produces savings in the carbon and water footprints. Conversely, for those that generate a greater footprint, we have arguments to evaluate when it can be more efficient to modify the consumption of foreign fruits and vegetables. Two complementary lines are required to conform a curbing emissions-water use strategy: production and consumption-side policies. We begin by considering consumer strategies; however, we should state that changes in consumption decisions are difficult to cause. This can be especially limiting when considering tropical fruits that represent 11% of total imported fruits (in euros). Regarding transferring information to consumers, a strategy could be to accentuate local consumption campaigns in those months in which the impact of trade is more negative. In addition, the message of the campaigns should regard the potential environmental impact mitigation and the health-based information that proves to be more effective in changing household's patterns [62]. Since patterns are complex and change for different product groups and the considered footprint, perhaps the best thing would be to have local and seasonal campaigns in time to avoid conveying confusing information to consumers if we want to mitigate the effects of teleconnection [63].

The significant changes in footprint found by the substitution between domestic and imported consumption of fruits and vegetables lead us to propose an environmental certification system. A simple eco-label informing the imported product footprint in comparison to the local consumption alternative (average, cleaner or dirtier) will be a nudge towards environmentally friendly consumption. This information would allow the consumer to know that when consuming imported pineapples in relation to local in-season fruits (oranges in January or mandarins in October), there is a smaller water impact. As with the challenges for other types of labels (particularly on footprints[64-67]), the proposed eco-label would need to track the produce and country, in addition to the season, on a monthly basis. Obviously, all these activities should be weighted by acknowledging the research on information campaigns and on their limits to change behavior in this complex topic[68, 69].

Certain production-and distribution policies should be implemented to ensure far-reaching changes. Supermarkets could nurture consumers' cleaner choices by launching a fruits and vegetables range that provides a sustainable basket of domestic and imported produce, without entering into conflict with households' freedom to choose. Another alternative could be carbon and water taxes on both domestic production and imports, which would encourage the shift towards consumption with a lower environmental footprint. Nevertheless, this type of policy encounters serious design and implementation problems for carbon (and water) border taxes[70, 71] and could conflict with WTO legislation. In addition, a carbon tax could have a limited effect by moderately increasing the price of agricultural products in the Spanish economy[33]; in addition, such a tax would be regressive since food is a very important part of the consumption basket of low income groups[72, 73].

Returning to the more technical aspects of the framework and the technical implementation presented, we recapitulate that the advantage of an MRIO is that it incorporates the total emissions, direct and indirect, associated with the carbon and water footprints of fruits and vegetables, without generating double counting and without needing to truncate the data. The practical limitations stem from the level of disaggregation of the environmental coefficients for the different products and the timing of these coefficients. In relation to the disaggregation, an improvement strategy for the future of alternative research could be the construction of hybrid IO-LCA models that would allow one to incorporate the impact detail in direct emissions of Scope 1, while striving to compute the remaining impacts through the MRIO[13]. In relation to the timing, in our case, only the fruit and vegetable imports of the Spanish economy have been temporized to the different months of the year. The improvements would derive from using timed environmental intensities[16] and, if possible, to disaggregate the agriculture sector temporarily, depending on the consumption of intermediate inputs required in each production period. For water, we have obtained the monthly consumptive (blue) water use by using the basins of monthly blue water consumption[74]. However, this information would only be useful for the analysis if the output data and the MRIO data, at least for the agriculture sector, were also obtained monthly, to obtain meaningful monthly water coefficients and transactions of goods. All these lines of research are promising, and their interest is supported by this research, which has opened new possibilities by highlighting the importance of the different environmental pressures obtained monthly. The use of an advanced and comprehensive tool, a multiregional input-output (MRIO) model, has also provided support.

ASSOCIATED CONTENT

Supporting Information (SI). The following files are available free of charge. Detailed methodology, trade analysis and monthly carbon/water footprints (PDF)

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Notes

The authors declare no competing financial interest

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REFERENCES

1. Spanish Statistical Office (INE), Households' expenditures survey. In Madrid, 2016. http://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176806&menu=ultiDatos&idp=1254735976608.
2. Ivanova, D.; Stadler, K.; Steen-Olsen, K.; Wood, R.; Vita, G.; Tukker, A.; Hertwich, E. G., Environmental Impact Assessment of Household Consumption. *Journal of Industrial Ecology* **2015**, n/a-n/a.
3. Kemp, K.; Insch, A.; Holdsworth, D. K.; Knight, J. G., Food miles: Do UK consumers actually care? *Food Policy* **2010,** *35*, (6), 504-513.
4. Weber, C. L.; Matthews, H. S., Food-Miles and the Relative Climate Impacts of Food Choices in the United States. *Environmental Science & Technology* **2008,** *42*, (10), 3508-3513.
5. Brooks, M.; Foster, C.; Holmes, M.; Wiltshire, J., Does consuming seasonal foods benefit the environment? Insights from recent research. *Nutrition Bulletin* **2011,** *36*, (4), 449-453.
6. Röös, E.; Karlsson, H., Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption. *Journal of Cleaner Production* **2013,** *59*, 63-72.
7. Michalský, M.; Hooda, P. S., Greenhouse gas emissions of imported and locally produced fruit and vegetable commodities: A quantitative assessment. *Environmental Science and Policy* **2015,** *48*, 32-43.
8. Edwards-Jones, G.; Milà i Canals, L.; Hounsome, N.; Truninger, M.; Koerber, G.; Hounsome, B.; Cross, P.; York, E. H.; Hospido, A.; Plassmann, K.; Harris, I. M.; Edwards, R. T.; Day, G. A. S.; Tomos, A. D.; Cowell, S. J.; Jones, D. L., Testing the assertion that ‘local food is best’: the challenges of an evidence-based approach. *Trends in Food Science & Technology* **2008,** *19*, (5), 265-274.
9. Coley, D.; Howard, M.; Winter, M., Food miles: time for a re-think? *British Food Journal* **2011,** *113*, (7), 919-934.
10. Drewnowski, A.; Rehm, C. D.; Martin, A.; Verger, E. O.; Voinnesson, M.; Imbert, P., Energy and nutrient density of foods in relation to their carbon footprint. *The American Journal of Clinical Nutrition* **2015,** *101*, (1), 184-191.
11. Garnett, T., Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? *Food Policy* **2011,** *36, Supplement 1*, (0), S23-S32.
12. Kissinger, M., Approaches for calculating a nation's food ecological footprint—The case of Canada. *Ecological Indicators* **2013,** *24*, (0), 366-374.
13. Virtanen, Y.; Kurppa, S.; Saarinen, M.; Katajajuuri, J.-M.; Usva, K.; Mäenpää, I.; Mäkelä, J.; Grönroos, J.; Nissinen, A., Carbon footprint of food – approaches from national input–output statistics and a LCA of a food portion. *Journal of Cleaner Production* **2011,** *19*, (16), 1849-1856.

14. Hospido, A.; i Canals, L. M.; McLaren, S.; Truninger, M.; Edwards-Jones, G.; Clift, R., The role of seasonality in lettuce consumption: a case study of environmental and social aspects. *Int J Life Cycle Assess* **2009,** *14*, (5), 381-391.

15. Dyer, J. A.; Desjardins, R. L.; Karimi-Zindashty, Y.; McConkey, B. G., Comparing fossil CO2 emissions from vegetable greenhouses in Canada with CO2 emissions from importing vegetables from the southern USA. *Energy for Sustainable Development* **2011,** *15*, (4), 451-459.

16. Pfister, S.; Bayer, P., Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production. *Journal of Cleaner Production* **2014,** *73*, 52-62.

17. Foster, C.; Guében, C.; Holmes, M.; Wiltshire, J.; Wynn, S., The environmental effects of seasonal food purchase: a raspberry case study. *Journal of Cleaner Production* **2014,** *73*, 269-274.

18. Theurl, M. C.; Haberl, H.; Erb, K.-H.; Lindenthal, T., Contrasted greenhouse gas emissions from local versus long-range tomato production. *Agronomy for Sustainable Development* **2014,** *34*, (3), 593-602.

19. Dietzenbacher, E.; Mukhopadhyay, K., An Empirical Examination of the Pollution Haven Hypothesis for India: Towards a Green Leontief Paradox? *Environmental and Resource Economics* **2007,** *36*, (4), 427-449.

20. Zhang, Y., Scale, Technique and Composition Effects in Trade-Related Carbon Emissions in China. *Environmental and Resource Economics* **2012,** *51*, (3), 371-389.

21. López, L.-A.; Arce, G.; Zafrilla, J., Financial Crisis, Virtual Carbon in Global Value Chains, and the Importance of Linkage Effects. The Spain–China Case. *Environmental Science & Technology* **2013,** *48*, (1), 36-44.

22. Tan, H.; Sun, A.; Lau, H., CO2 embodiment in China–Australia trade: The drivers and implications. *Energy Policy* **2013,** *61*, 1212-1220.

23. Arto, I.; Roca, J.; Serrano, M., Measuring emissions avoided by international trade: Accounting for price differences. *Ecological Economics* **2014,** *97*, 93-100.

24. Liu, Z.; Song, P.; Mao, X., Accounting the effects of WTO accession on trade-embodied emissions: Evidence from China. *Journal of Cleaner Production* **2016,** *139*, 1383-1390.

25. Liu, Z.; Davis, S. J.; Feng, K.; Hubacek, K.; Liang, S.; Anadon, L. D.; Chen, B.; Liu, J.; Yan, J.; Guan, D., Targeted opportunities to address the climate-trade dilemma in China. *Nature Clim. Change* **2016,** *6*, (2), 201-206.

26. Owen, A.; Scott, K.; Barrett, J., Identifying critical supply chains and final products: An input-output approach to exploring the energy-water-food nexus. *Applied Energy* **2018,** *210*, 632-642.

27. White, D. J.; Hubacek, K.; Feng, K.; Sun, L.; Meng, B., The Water-Energy-Food Nexus in East Asia: A tele-connected value chain analysis using inter-regional input-output analysis. *Applied Energy* **2018,** *210*, 550-567.

28. Page, G.; Ridoutt, B.; Bellotti, B., Carbon and water footprint tradeoffs in fresh tomato production. *Journal of Cleaner Production* **2012,** *32*, 219-226.

29. Payen, S.; Basset-Mens, C.; Perret, S., LCA of local and imported tomato: An energy and water trade-off. *Journal of Cleaner Production* **2015,** *87*, (1), 139-148.

30. Stoessel, F.; Juraske, R.; Pfister, S.; Hellweg, S., Life Cycle Inventory and Carbon and Water FoodPrint of Fruits and Vegetables: Application to a Swiss Retailer. *Environmental Science & Technology* **2012,** *46*, (6), 3253-3262.

31. Miller, R. E.; Blair, P. D., *Input-Output Analysis: Foundations and Extensions*. Cambridge University Press: Cambridge, UK, 2009.

32. Davis, S. J.; Peters, G. P.; Caldeira, K., The supply chain of CO2 emissions. *Proceedings of the National Academy of Sciences* **2011,** *108*, (45), 18554-18559.

33. López, L.-A.; Cadarso, M.-A.; Gómez, N.; Tobarra, M.-Á., Food miles, carbon footprint and global value chains for Spanish agriculture: assessing the impact of a carbon border tax. *Journal of Cleaner Production* **2015,** *103*, 423-436.

34. Cazcarro, I.; Duarte, R.; Sánchez Chóliz, J., Tracking Water Footprints at the Micro and Meso Scale: An Application to Spanish Tourism by Regions and Municipalities. *Journal of Industrial Ecology* **2016,** *20*, (3), 446-461.

35. Wiedmann, T. O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K., The material footprint of nations. *Proceedings of the National Academy of Sciences* **2013**, 112, (20), 6271-6276.

36. Arto, I.; Capellán-Pérez, I.; Lago, R.; Bueno, G.; Bermejo, R., The energy requirements of a developed world. *Energy for Sustainable Development* **2016,** *33*, 1-13.

37. Oita, A.; Malik, A.; Kanemoto, K.; Geschke, A.; Nishijima, S.; Lenzen, M., Substantial nitrogen pollution embedded in international trade. *Nature Geosci* **2016,** *9*, (2), 111-115.

38. Avelino, A. F. T., Disaggregating input–output tables in time: the temporal input–output framework. *Economic Systems Research* **2017**, 1-22.

39. Dietzenbacher, E.; Lenzen, M.; Los, B.; Guan, D.; Lahr, M. L.; Sancho, F.; Suh, S.; Yang, C., INPUT–OUTPUT ANALYSIS: THE NEXT 25 YEARS. *Economic Systems Research* **2013,** *25*, (4), 369-389.

40. Lenzen, M., AGGREGATION VERSUS DISAGGREGATION IN INPUT–OUTPUT ANALYSIS OF THE ENVIRONMENT. *Economic Systems Research* **2011,** *23*, (1), 73-89.

41. Kanemoto, K.; Lenzen, M.; Peters, G. P.; Moran, D. D.; Geschke, A., Frameworks for comparing emissions associated with production, consumption, and international trade. *Environmental Science & Technology* **2012,** *46*, (1), 172–179.

42. Peters, G. P.; Davis, S. J.; Andrew, R., A synthesis of carbon in international trade. *Biogeosciences* **2012,** *9*, (8), 3247-3276.

43. Andrew, R. M.; Peters, G. P., A MULTI-REGION INPUT–OUTPUT TABLE BASED ON THE GLOBAL TRADE ANALYSIS PROJECT DATABASE (GTAP-MRIO). *Economic Systems Research* **2013,** *25*, (1), 99-121.

44. Su, B.; Ang, B. W., Multi-region input–output analysis of CO2 emissions embodied in trade: The feedback effects. *Ecological Economics* **2011,** *71*, (0), 42-53.

45. Davis, S. J.; Caldeira, K., Consumption-based accounting of CO2 emissions. *Proceedings of the National Academy of Sciences of the United States of America* **2010,** *107*, (12), 5687-5692.

46. Feng, K.; Davis, S. J.; Sun, L.; Li, X.; Guan, D.; Liu, W.; Liu, Z.; Hubacek, K., Outsourcing CO2 within China. *Proceedings of the National Academy of Sciences* **2013,** *110*, (28), 11654-11659.

47. Tukker, A.; Dietzenbacher, E., GLOBAL MULTIREGIONAL INPUT–OUTPUT FRAMEWORKS: AN INTRODUCTION AND OUTLOOK. *Economic Systems Research* **2013,** *25*, (1), 1-19.

48. EXIOBASE Consortium, EXIOBASE v.2.2. In 2015.

49. Tukker, A.; de Koning, A.; Wood, R.; Hawkins, T.; Lutter, S.; Acosta, J.; Rueda Cantuche, J. M.; Bouwmeester, M.; Oosterhaven, J.; Drosdowski, T.; Kuenen, J., EXIOPOL – DEVELOPMENT AND ILLUSTRATIVE ANALYSES OF A DETAILED GLOBAL MR EE SUT/IOT. *Economic Systems Research* **2013,** *25*, (1), 50-70.

50. Wood, R.; Stadler, K.; Bulavskaya, T.; Lutter, S.; Giljum, S.; de Koning, A.; Kuenen, J.; Schütz, H.; Acosta-Fernández, J.; Usubiaga, A.; Simas, M.; Ivanova, O.; Weinzettel, J.; Schmidt, H. J.; Merciai, S.; Tukker, A., Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. *Sustainability* **2015,** *7*, (1), 138-163.

51. Lenzen, M.; Moran, D.; Bhaduri, A.; Kanemoto, K.; Bekchanov, M.; Geschke, A.; Foran, B., International trade of scarce water. *Ecological Economics* **2013,** *94*, 78-85.

52. FAO, AQUASTAT Main Database. In Food and Agriculture Organization of the United Nations (FAO), Ed. 2017.

53. Aduanas, D. G. d., Datos estadísticos de comercio exterior. In 2011.

54. FAO, *Statistical Yearbook.* Food and Agriculture Organization of United Nations: Rome, 2013.

55. Stadler, K.; Steen-Olsen, K.; Wood, R., THE 'REST OF THE WORLD' – ESTIMATING THE ECONOMIC STRUCTURE OF MISSING REGIONS IN GLOBAL MULTI-REGIONAL INPUT–OUTPUT TABLES. *Economic Systems Research* **2014,** *26*, (3), 303-326.

56. Tukker, A.; Cohen, M. J.; Hubacek, K.; Mont, O., The Impacts of household consumption and options for change. *Journal of Industrial Ecology* **2010,** *14*, (1), 13-30.

57. Tukker, A.; Goldbohm, R. A.; De Koning, A.; Verheijden, M.; Kleijn, R.; Wolf, O.; Pérez-Domínguez, I.; Rueda-Cantuche, J. M., Environmental impacts of changes to healthier diets in Europe. *Ecological Economics* **2011,** *70*, (10), 1776-1788.

58. Pairotti, M. B.; Cerutti, A. K.; Martini, F.; Vesce, E.; Padovan, D.; Beltramo, R., Energy consumption and GHG emission of the Mediterranean diet: A systemic assessment using a hybrid LCA-IO method. *Journal of Cleaner Production* **2015,** *103*, 507-516.

59. Cazcarro, I.; Duarte, R.; Sánchez-Chóliz, J., Water Flows in the Spanish Economy: Agri-Food Sectors, Trade and Households Diets in an Input-Output Framework. *Environmental Science & Technology* **2012,** *46*, (12), 6530-6538.

60. Macdiarmid, J. I., Seasonality and dietary requirements: will eating seasonal food contribute to health and environmental sustainability? *Proceedings of the Nutrition Society* **2014,** *73*, (03), 368-375.

61. Hiç, C.; Pradhan, P.; Rybski, D.; Kropp, J. P., Food Surplus and Its Climate Burdens. *Environmental Science & Technology* **2016,** *50*, (8), 4269-4277.

62. Asensio, O. I.; Delmas, M. A., Nonprice incentives and energy conservation. *Proceedings of the National Academy of Sciences* **2015,** *112*, (6), E510-E515.

63. Hubacek, K.; Feng, K.; Minx, J. C.; Pfister, S.; Zhou, N., Teleconnecting consumption to environmental impacts at multiple spatial scales. *Journal of Industrial Ecology* **2014,** *18*, (1), 7-9.

64. Quack, D.; Griesshammer, R.; Teufel, J. *Requirements on Consumer Information about Product Carbon Footprint*; Öko-Institut e.V. (Institute for Applied Ecology): Freiburg, 2010.

65. Leach, A. M.; Emery, K. A.; Gephart, J.; Davis, K. F.; Erisman, J. W.; Leip, A.; Pace, M. L.; D'Odorico, P.; Carr, J.; Noll, L. C.; Castner, E.; Galloway, J. N., Environmental impact food labels combining carbon, nitrogen, and water footprints. *Food Policy* **2016,** *61*, (Supplement C), 213-223.

66. Thøgersen, J.; Nielsen, K. S., A better carbon footprint label. *Journal of Cleaner Production* **2016,** *125*, (Supplement C), 86-94.

67. Upham, P.; Dendler, L.; Bleda, M., Carbon labelling of grocery products: public perceptions and potential emissions reductions. *Journal of Cleaner Production* **2011,** *19*, (4), 348-355.

68. Thøgersen, J., Inducing green behaviour. *Nature Climate Change* **2013,** *3*, 100.

69. Akenji, L., Consumer scapegoatism and limits to green consumerism. *Journal of Cleaner Production* **2014,** *63*, 13-23.

70. Branger, F.; Quirion, P., Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies. *Ecological Economics* **2014,** *99*, 29-39.

71. Sakai, M.; Barrett, J., Border carbon adjustments: Addressing emissions embodied in trade. *Energy Policy* **2016,** *92*, 102-110.

72. López, L. A.; Arce, G.; Morenate, M.; Monsalve, F., Assessing the Inequality of Spanish Households through the Carbon Footprint: The 21st Century Great Recession Effect. *Journal of Industrial Ecology* **2016,** *20*, (3), 571-581.

73. Wang, Q.; Liang, Q.-M.; Wang, B.; Zhong, F.-X., Impact of household expenditures on CO2 emissions in China: Income-determined or lifestyle-driven? *Natural Hazards* **2016,** *84*, (1), 353-379.

74. Hoekstra, A. Y.; Mekonnen, M. M., The water footprint of humanity. *Proceedings of the National Academy of Sciences* **2012,** *109*, (9), 3232-3237.