Environmental Science & Technology

Policy Analysis

pubs.acs.org/est

Carbon, Land, and Water Footprint Accounts for the European Union: Consumption, Production, and Displacements through International Trade

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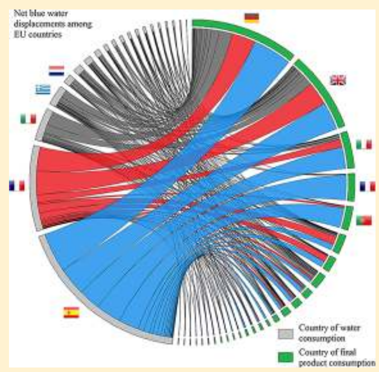
Supporting Information

ABSTRACT: A nation's consumption of goods and services causes various environmental pressures all over the world due to international trade. We use a multiregional input−output model to assess three kinds of environmental footprints for the member states of the European Union. Footprints are indicators that take the consumer responsibility approach to account for the total direct and indirect effects of a product or consumption activity. We quantify the total environmental pressures (greenhouse gas emissions: carbon footprint; appropriation of biologically productive land and water area: land footprint; and freshwater consumption: water footprint) caused by consumption in the EU. We find that the consumption activities by an average EU citizen in 2004 led to 13.3 tCO_2e of induced greenhouse gas emissions, appropriation of 2.53 gha (hectares of land with global-average biological productivity), and consumption of 179 m^3 of blue water (ground and surface water). By comparison, the global averages were 5.7 tCO_2e, 1.23 gha, and 163 m^3 blue water, respectively. Overall, the EU displaced all three types of environmental pressures to the rest of the world, through imports of products with embodied pressures. Looking at intra-EU displacements only, the UK was the most important displacer overall, while the largest net exporters of embodied environmental pressures were Poland (greenhouse gases), France (land), and Spain (freshwater).



INTRODUCTION

Among the many environmental concerns the global community will be faced with in the 21st century, three major challenges stand out as particularly important. First, considerable efforts are currently directed toward the task of minimizing anthropogenic greenhouse gas (GHG) emissions and the potential harmful climate change effects caused by them. Furthermore, the rapid growth in population and material wealth over the previous century has led to widespread concerns about the state of two resources of vital importance to all life on earth: freshwater and biologically productive land. These three areas of concern are all highly important, and, though essentially different, they are all interconnected and mutually influencing each other, and direct efforts to alleviate one problem might well imply hidden trade-offs with others. As such, it is reasonable to suggest that these (and ideally other) environmental challenges should be assessed simultaneously when politicians and leaders are shaping policies and making investments with a sustainable future in mind.

However, assessing the environmental impacts of GHG emissions and human appropriation of land and water at the macro level is nontrivial, and several approaches exist. Based on the argument that environmental pressures are ultimately driven by consumption of goods and services, several studies and pressure indicators follow the principle of consumer responsibility and attempt to allocate full life-cycle environmental responsibilities of purchased commodities to final consumers.[1] As a way to communicate this idea to a wider audience, the "footprint" term has been adopted for various quantitative measures of environmental stress that adhere to the principle of consumer responsibility. Galli et al.[2] define a "Footprint Family" of three of the most well-recognized footprints available, to be used in assessments of the three environmental issues discussed previously. The Footprint Family includes the carbon footprint (CF), the Ecological Footprint (EF), and the water footprint (WF). The carbon footprint is a measure of total GHG emissions embodied in consumption, measured in tons of CO_2-equivalents.[3] The Ecological Footprint quantifies embodied biological resources in terms of required area of biologically productive land. The measurement unit is the global hectare (gha), which is defined as a hectare of average productivity.[4] Finally, the water footprint measures direct and indirect freshwater requirements in m^3,

Received: May 15, 2012
Revised: September 10, 2012
Accepted: September 26, 2012
Published: September 26, 2012

distinguishing among green water (direct rainwater consumption by plants), blue water (ground and surface water), and gray water (a measure of water pollution expressed as the water requirements to dilute emissions).[5]

Footprint indicators are commonly used for assessments at the individual or company level; however for policy making purposes it is useful to construct footprint accounts for countries or regions instead. Such national footprint accounts can provide understanding of the relative importance and nature of a country's impacts in a global perspective, and shed light on the underlying drivers of these impacts. Moreover, the footprint approach allows a quantification of impacts of domestic consumption on nature worldwide. Several attempts to construct national footprint accounts have been made: Global Footprint Network (GFN) regularly constructs national accounts of Ecological Footprints for most countries of the world, addressing both land use and CO_2 emissions;[6] the Water Footprint Network has made similar accounts for water footprints;[7] and Hertwich and Peters[3] presented carbon footprint accounts, which were later updated by Peters et al.[8,9] and are displayed online at ref 10.

Consumption-based accounting adds considerably to analysis complexity compared to territorial accounts, because products may accumulate significant embodied impacts far upstream in complex international supply chains. Multiregional input–output (MRIO) analysis is able to account for complete supply chain effects by taking a top-down approach. While MRIO analysis has been systematically applied in carbon footprint calculations, the Ecological Footprint and the water footprint were developed as bottom-up approaches based on direct land and water use of key sectors. Still, there have been several studies that have used input–output (IO) techniques for measuring EF and WF. Lenzen and Murray[11] and Wiedmann et al.[12] demonstrated the advantages of using IO for EF accounting. McDonald and Patterson[13] used MRIO to analyze regional interdependencies for New Zealand's EF, while Feng et al.[14] used a global MRIO model to calculate WF, following similar MRIO-based analyses for China.[15,16] A material footprint, quantifying the cumulative amount of material natural resources (domestic extraction used all over the world) embodied in the consumption of the EU, has been estimated by ref 17 and denoted as raw material consumption, which belongs to a group of economy-wide material flow indicators.

In this study we analyze environmental footprints of the EU27 countries, and how environmental pressures are displaced among them and to the rest of the world. We present comprehensive accounts of the three footprints, calculated using a common model framework—based on a global MRIO model—to account for supply chain effects (see the Supporting Information (SI) for detailed accounts). A drawback to input–output based EF and WF assessments has been loss of detail at the product level, because land and water use depend heavily on agricultural products, which are usually aggregated into a few bulk categories in input–output tables. The extended MRIO model used in this work partially overcomes the traditional disadvantages of low product detail within the MRIO system by including satellite accounts track the production and international trade of a range of specific primary crop and forestry products.[18] By quantifying three different footprint indicators simultaneously and under a common methodological framework, we are able to assess pressures on three different compartments of the environment in a coherent manner, allowing a fuller picture of the true environmental pressures put on the planet by consumption activities in the EU. This should help to avoid environmental pressure shifting caused by focusing on a sole type of environmental problem.

We include carbon footprints (CF), blue water footprints (WF_b), and land footprints (LF) in our analysis. The LF is equivalent to the Ecological Footprint excluding carbon uptake land, since this is directly related to CO_2 emissions already captured by the CF.[19] We also chose to focus on the blue component of the water footprint, since gray water is not a measure of water consumption in the direct physical sense but of water pollution, and green water is direct rainwater consumption, which as argued by ref 20 is a pressure that would be double counted in combination with the LF; however the interested reader can find results for the complete EF and WF indicators, as well as a discussion of the various footprint indicators, in the SI. Note that according to the "Driver, Pressure, State, Impact, Response" (DPSIR) framework used by the European Environmental Agency,[21] these are all pressure indicators. They present a single quantitative measure, which can be broken down in more detail, but they do not assess the resulting impacts.

A key interest for this analysis has been the displacement of environmental pressure through trade. We speak of a displacement when the environmental pressure occurs in another country than the country of final consumption of the product whose production is the immediate cause of the environmental pressure, following the discussion of land use studies.[22] In other words, if a pressure is displaced from country A to country B, emissions, land use, or water use occurring in country B serve the consumption in country A. Previous research on displacements of environmental pressures through international trade has indicated that Europe generally tends to have net imports of embodied pressures from other regions of the world. For the water footprint, the results of Hoekstra and Mekonnen[7] indicate that a large share of the water footprint of European countries (especially in western Europe) tends to be external compared to developing countries. Peters and Hertwich[23] showed that many EU countries are net importers of embodied CO_2 emissions, and that a significant share of this displacement was to fellow member states. Weinzettel et al.[19] found that Europe overall displaces land use to other regions of the world, especially Latin America and Asia.

In the following section, the model is described. This is followed by a section presenting the results of our analysis, while the final section provides a discussion of our main findings.

METHODS AND DATA

The analysis was carried out using a global MRIO model based on the GTAP 7 database,[24] following the method described by Peters et al.[25] The model year is 2004, as this is the reference year for the GTAP 7 database. The model tracks economic transactions among actors in the global economy, aggregated into 57 economic sectors in 113 regions, allowing the establishment of a model of sectoral interdependencies among regions through the application of the Leontief inverse.

The MRIO framework allows the tracking of environmental impacts through complex international supply chains. However, MRIO tables describe only aggregated groups of products and sectors. To provide a higher level of detail including specific crops, we created a parallel system to explicitly track the production and trade of primary products of agriculture and forestry, since this production accounts for the majority of land and water use globally.[7,26] Compared to a full disaggregation of these sectors in the MRIO model, which would require extensive new data and labor for a long list of products, our method is a compromise.

We followed the approach suggested by Ewing et al.,[27] and created an extension matrix $P^{use,x}$ with rows representing sales of each primary product (in physical units) from each region, distributed to the regions and sectors which purchase them in their primary form, in the columns. There is an additional matrix $P^{use,y}$ for direct purchases by the final demand sector. The columns thus follow the dimensions of the MRIO system, while the number of products and countries on the rows can be as detailed as desired. A more comprehensive presentation of the model can be found in the SI.

The allocation of agricultural products to intermediate and final consumers in the extension matrix allows the utilization of the extensive amounts of data available for these products.[27] We used data on production and international trade from the Food and Agriculture Organization of the United Nations (FAO) to allocate products to consuming countries.[28] We also used information on consumption by specific sectors, including the use of agricultural products such as seed and livestock feed. The remainder was allocated based on the sales structure of the corresponding sector in the MRIO model.

Our environmental extension matrices thus represent the use of primary products, produced in individual countries, by specific industries and final consumers. Using the standard input−output methodology we were then able to estimate total national requirements of specific primary products produced in specific countries. This bill of requirements was then converted to associated footprints by applying crop- and country-specific land and water use intensities (see the SI for more on these). Finally, footprints not directly related to primary products were calculated from a second set of extension matrices following traditional practice for environmentally extended MRIO, and the two contributions were added to arrive at a total. For more details and a mathematical description of the method, see the SI and ref 18.

■ RESULTS

The total carbon footprint of the EU in 2004 was 6.5 billion tons CO_2-equivalents ($GtCO_2e$), representing 18% of the world total (Table 1). As the EU constituted 7.6% of the global population, its average CF of 13.3 tCO_2e/p was well over twice the global average. Similarly, the EU's land footprint of 2.53 gha/p was just over twice that of the world overall. In terms of blue water the EU footprint of 179 m^3/p was only 10% above the global average.

Table 1. Total and per Capita Footprints for the EU and the Rest of the World (RoW) in 2004, Displacements within the EU, and between the EU as a Whole and the Rest of the World

	CF		LF		WF_b	
	$GtCO_2e$	tCO_2e/p	Ggha	gha/p	Gm^3	m^3/p
EU	6.5	13.3	1.23	2.53	87	179
RoW	30.0	5.1	6.58	1.11	958	162
world	36.5	5.7	7.82	1.22	1045	163
displacements						
among EU countries	0.79		0.20		9	
from EU to RoW	2.01		0.38		37	
from RoW to EU	0.50		0.10		4	

The trade analysis quantifies environmental pressures occurring in other countries to serve domestic final consumption of goods and services. When looking at the exchanges between the EU and the rest of the world, the analysis showed that the EU displaced far more pressures to the rest of the world (RoW) than the RoW displaced to the EU. EU displacements to RoW were about a factor of 4 higher than the corresponding displacements to the EU for CF and LF, and a factor of 9 higher for WF_b.

In the following paragraphs we examine the footprint results for the EU member countries, and how environmental pressures are shifted internally in the EU through trade.

Footprints for the EU27 Member States. *Carbon Footprints.* All EU countries except for Romania had CF per capita above the global average. The very high footprint of 41.6 tCO_2e/p for Luxembourg should be taken cautiously due to Luxembourg's unique economic structure with parts of the work force commuting from neighboring countries, although the high affluence level of Luxembourg would also predict high CF levels.[3] Excluding Luxembourg, the disparity among member states was still rather large, ranging from 19.8 tCO_2e/p for Belgium to only 5.6 tCO_2e/p for Romania.

The degree to which individual countries imported and exported embodied GHG emissions varied considerably, as shown in Figure 1. For the EU overall, 57% of the emissions constituting its total CF occurred in the countries of final consumption, 12% were displaced internally, and 31% occurred in countries outside the EU. Though the EU overall was a net importer of embodied emissions from the rest of the world, five individual member states (the Czech Republic, Poland, Estonia, Bulgaria, and Romania) were net exporters of embodied emissions overall.

Land Footprints. All EU countries were 35% or more above the global average land footprint of 1.23 gha/p, except for Malta, which was close to the global average (Figure 1). In the upper end of the footprint ranking we again find Luxembourg standing out, this time joined by the Nordic countries Finland, Sweden, and Denmark. Of the four, Finland was especially high at 6.8 gha/p—2.3 times above EU and 4.8 times above global averages. From the domestic pressure perspective, land use per capita was especially high in Finland, Sweden, Estonia, and Latvia. This was mostly due to large forestry and (particularly in Estonia's case) fishing industries, combined with the lowest population densities within the EU27 region which serve to exalt the level of land use per capita.

The geographic distribution of the land use that formed the total LF followed a pattern similar to that for CF. Fifty-three percent of the EU's LF was associated with domestic land use, 16% was associated with land use in other EU countries, and 31% was land used outside the EU. Eleven EU countries were net exporters of embodied land use (Estonia, Finland, Latvia, and Sweden had the highest net exports per capita), but since the more populous countries were generally importers (Poland was an exception), the overall result for the EU was a net displacement of land use to other countries. Malta and Cyprus were especially dependent on displacing land use to other countries due to their dry climate.

Blue Water Footprints. There were very large differences among individual EU countries due to different biophysical conditions and consumption patterns, with footprints ranging

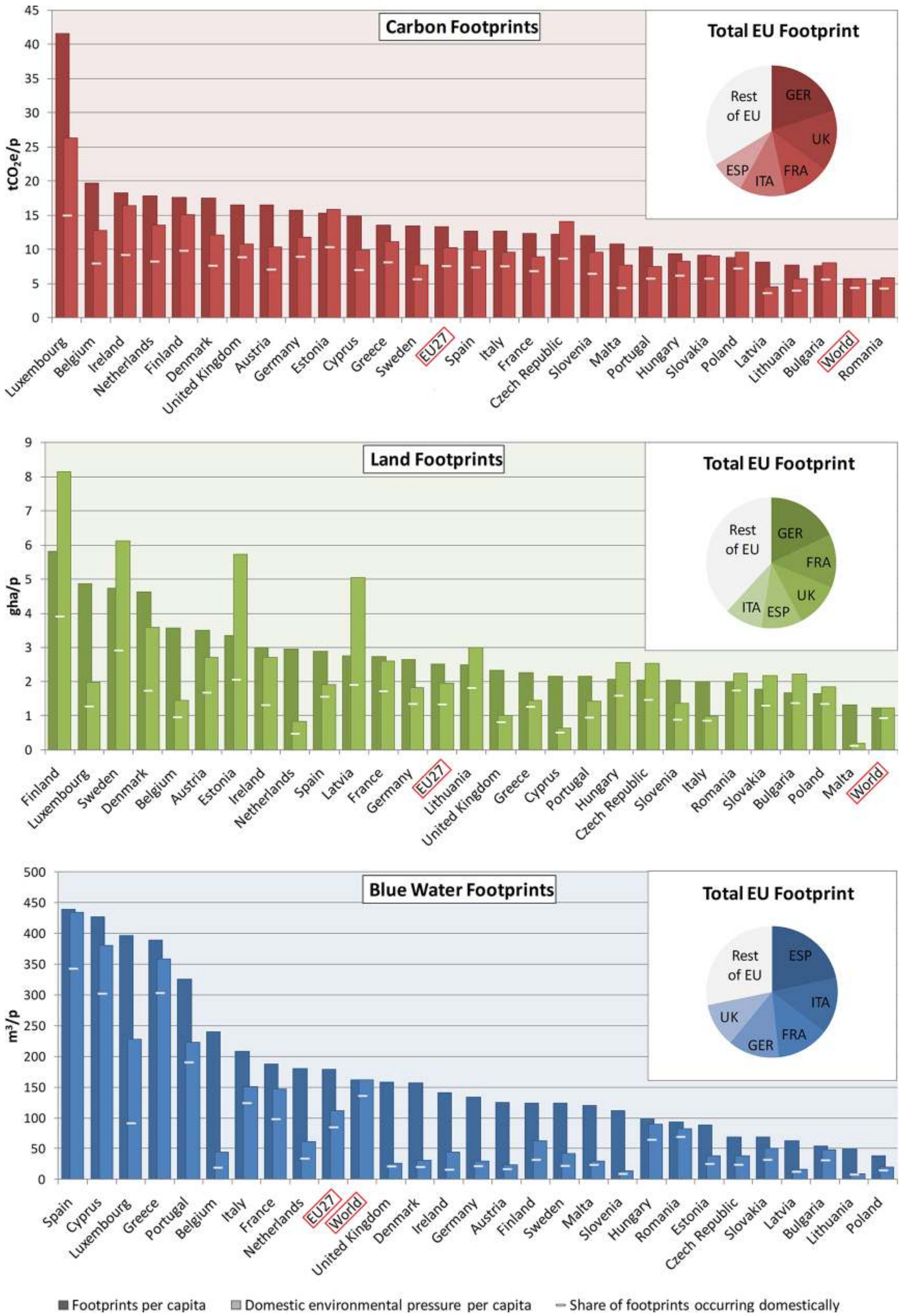


Figure 1. Carbon, land, and blue water footprints (darker columns) and the environmental pressures occurring within the borders of each country (lighter columns) per capita for the individual EU27 countries, as well as EU27 and global averages. The white markers show the part of the footprint which occurs as pressure on the domestic territory, or in other words the part of the environmental pressure on the domestic territory which was induced by domestic final demand. The pie charts show the top five contributing countries to the EU's total footprints.

from 438 m^3/p for Spain to as little as 39 m^3/p—less than a quarter of the global average—for Poland. In fact, most EU countries had WF_b levels per person below the global average, but the very high footprints of Mediterranean countries, where

Table 2. Net Displacements of Environmental Pressures by Each EU Country to the Rest of the EU[a]

	CF		LF		WF_b	
	$MtCO_2e$	tCO_2e/p	Mgha	gha/p	Mm^3	m^3/p
Austria	14.8	**1.8**	1.6	0.2	200	**24.5**
Belgium	2.1	0.2	6.9	**0.7**	238	**22.9**
Bulgaria	−7.3	−0.9	−2.7	−0.3	−28	−3.6
Cyprus	0.6	0.7	0.4	0.5	−16	−19.5
Czech Republic	−23.7	−2.3	−5.4	−0.5	23	2.2
Denmark	2.5	0.5	−0.8	−0.1	110	20.3
Estonia	−2.9	−2.2	−2.5	−1.8	3	2.0
Finland	−7.4	−1.4	−10.4	−2.0	−11	−2.1
France	**23.6**	0.4	−16.4	−0.3	−773	−12.8
Germany	9.9	0.1	10.0	0.1	**1390**	16.8
Greece	1.7	0.2	3.0	0.3	−245	−22.1
Hungary	−3.1	−0.3	−4.6	−0.5	−92	−9.1
Ireland	−7.6	−1.9	−1.8	−0.4	18	4.5
Italy	16.4	0.3	**18.7**	0.3	50	0.9
Latvia	2.0	0.8	−4.6	−2.0	11	4.8
Lithuania	0.5	0.1	−1.5	−0.4	20	5.9
Luxembourg	0.6	1.2	0.5	**1.2**	−12	−26.8
Malta	0.1	0.2	0.1	0.3	8	20.3
Netherlands	−20.9	−1.3	9.7	0.6	76	4.7
Poland	−43.3	−1.1	−9.8	−0.3	74	1.9
Portugal	4.4	0.4	1.4	0.1	235	22.5
Romania	−11.0	−0.5	−5.5	−0.3	−110	−5.1
Slovakia	−4.0	−0.7	−2.0	−0.4	−31	−5.7
Slovenia	0.6	0.3	0.5	0.2	33	16.8
Spain	−12.4	−0.3	6.5	0.2	−2346	−55.0
Sweden	15.9	**1.8**	−9.9	−1.1	97	10.7
United Kingdom	**48.2**	0.8	**18.7**	0.3	**1078**	18.1

[a]The columns of country totals all sum to zero, except for rounding. The two highest and lowest values in each column are highlighted by bold text.

Table 3. Top Five Net Pressure Displacements (ND) between EU Member States[a]

CF ($MtCO_2e$)			LF (Mgha)			WF_b (Mm^3)		
displacement from/to			displacement from/to			displacement from/to		
imported products	ND	GD	imported products	ND	GD	imported products	ND	GD
Germany/Poland	12.5	17.8	Italy/France	6.25	7.20	Germany/Spain	542	573
chem., rubber, plast. prd.		10%	wheat		22%	vegetables, fruits, nuts		58%
machinery and equipmt. nec.[b]		10%	cattle, sheep, goats, horses		20%	food products nec.		9%
motor vehicles and parts		9%	cereal grains nec.		15%	beverages and tobacco prod.		8%
Germany/Czech Republic	9.7	13.6	Germany/Poland	3.89	4.68	UK/Spain	387	405
electricity		23%	wood products		52%	vegetables, fruits, nuts		46%
machinery and equipmt. nec.		12%	food products nec.		11%	food products nec.		10%
chem., rubber, plast. prd.		11%	motor veh. and parts		4%	beverages and tobacco prod.		10%
France/Germany	8.6	23.8	UK/Sweden	3.39	3.50	France/Spain	348	637
chem., rubber, plast. prd.		18%	wood products		56%	vegetables, fruits, nuts		40%
motor vehicles and parts		12%	paper products, publishing		23%	food products nec.		15%
machinery and equipmt. nec.		11%	business services nec.		3%	animal products nec.		6%
UK/Germany	8.5	20.3	UK/France	3.09	4.26	Germany/France	327	396
motor vehicles and parts		20%	cereal grains nec.		17%	cereal grains nec.		15%
chem., rubber, plast. prd.		18%	food products nec.		15%	motor veh. and parts		11%
machinery and equipmt. nec.		10%	beverages and tobacco prod.		12%	chem., rubber, plast. prod.		10%
UK/Spain	7.6	13.6	Netherlands/Germany	3.09	4.18	UK/France	325	355
air transport		23%	fishing		32%	cereal grains nec.		24%
transport nec.		14%	cereal grains nec.		14%	motor vehicles and parts		14%
motor vehicles and parts		11%	food products nec.		10%	chem., rubber, plast. prod.		10%

[a]The gross displacement (GD) value corresponding to each displacement is also shown, as well as which products imported by the displacing country that contribute most to the total GD. [b]Not elsewhere classified.

agricultural systems are more dependent on irrigation, pulled the footprint per person for the EU27 overall above the global average. Spain alone, with only 9% of the EU population, contributed 21% of the EU's total WF_b. Finally, an interesting feature of Figure 1 is that the ten former East Bloc countries in the EU were also the ten countries with the lowest WF_b per capita.

A higher degree of pressure displacement was found for WF_b than for the other footprints: 42% of the EU's blue water footprint was water used outside the EU, while 47% was domestic water use and 10% was water use displaced between EU countries. All EU countries were net importers of embodied blue water, even the countries with very high levels of domestic blue water use turned out to have footprints that were even higher. Indeed, as seen in Table 1 the flows of embodied blue water into Europe were large compared to the outflow and also compared to the flows of embodied carbon and land use. Although the average EU WF_b per capita is about the same as the global average, this is at the same time the footprint where the EU consumption causes relatively the most displacements to the rest of the world. Both these observations are explained by the low levels of domestic blue water consumption per capita in European countries; see Tables S-1 and S-2 of the SI.

Footprints Shifted Internally among EU Countries. Though the EU overall displaced all three pressure types to the rest of the world, the detailed trade analysis showed that there were also significant shifts of pressures internally in the EU. Table 2 shows the individual member states' net imports of embodied pressures from other EU countries. In the following paragraphs, these shifts through trade are explored and results of the contribution analysis are presented to identify which products led to the largest pressure displacements. Table 3 lists the largest net pressure displacements between EU countries, and the most important traded products related to these displacements, while Table 4 shows the largest product-specific displacements between EU countries. Note that whereas Table 4 compares gross flows, Tables 2 and 3 compare net flows of embodied pressures between countries, i.e. the ranking is performed on the difference between the reciprocal displacements between each pair of countries.

Table 4. Top Five Product-Specific Gross Pressure Displacements (GD) between EU Member States, i.e. the Products Imported by One EU Country That Cause the Largest Environmental Pressure in a Fellow EU Country, and the Absolute Values of These Displacements

CF ($MtCO_2e$)		LF (Mgha)		WF_b (Mm^3)	
displacement from/to		displacement from/to		displacement from/to	
imported products	GD	imported products	GD	imported products	GD
Italy/France	4.7	Germany/Poland	2.4	Germany/Spain	331
cattle, sheep, goats, horses		wood products		vegetables, fruits, nuts	
France/Germany	4.4	UK/Sweden	2.0	France/Spain	256
chem., rubber, plastic prod.		wood products		vegetables, fruits, nuts	
UK/Germany	4.0	Italy/France	1.6	UK/Spain	185
motor vehicles and parts		wood products		vegetables, fruits, nuts	
UK/Germany	3.6	Italy/France	1.4	Italy/Spain	101
chem., rubber, plastic prod.		cattle, sheep, goats, horses		vegetables, fruits, nuts	
Germany/Netherlands	3.4	UK/Poland	1.4	Spain/France	97
petroleum, coal products		wood products		cereal grains nec.[a]	

[a]Not elsewhere classified.

Carbon Footprints. Comparing countries overall, Table 2 shows that Poland was by far the largest net exporter of embodied GHG emissions, while the United Kingdom held an even clearer position as the largest net importer. Per capita, Austria and Sweden had the highest net imports. The net result for each country consists of a sum of net exchanges with the remaining member states. Thus, for instance, France's large net import of embodied GHG emissions actually included a significant net export (2.6 $MtCO_2e$) to Italy (see SI Table S-3 for details).

The single largest net export of embodied GHG emissions between two EU countries was from Poland to Germany (12.5 $MtCO_2e$, see Table 3). Overall, Germany was an important trader of embodied CF, as apparent in Table 3. The second largest exchange was emissions embodied in German imports from the Czech Republic, a large part of which was embodied in electricity imports. The emissions embodied in the gross electricity exports from the Czech Republic to Germany amounted to 3.1 $MtCO_2e$. This was still less than the emissions embodied in the largest single product flow, "Bovine cattle, sheep and goats, horses" exports from France to Italy (4.7 $MtCO_2e$), as reported in Table 4. On the list of largest product-specific flows of embodied emissions we also find motor vehicle exports from Germany to the UK, suggesting the importance of the German automotive sector on the overall carbon footprints in European countries.

Land Footprints. In total, the main net importers of embodied LF were the United Kingdom and Italy. France had the largest embodied land use exports (absorbed land use in the terminology of ref 29). Per capita, the main net exporters of embodied LF were the northeastern cluster of Latvia, Estonia, Finland, and Sweden. The biggest net importers of embodied LF per capita were the small and densely populated Benelux (Belgium, Netherlands, Luxembourg) countries, as evident from Table 2.

All EU countries were net exporters of embodied land use to some EU countries, while having net imports from others. For example, the UK's large net import from the rest of the EU also contained a significant net export of embodied land use to Spain; 0.4 Mgha (see SI Table S-4). Malta stands out with net embodied land use imports from all EU countries except Greece.

By far the largest net shift of embodied land use between EU countries, shown in Table 3, was Italy's displacements to France. Important contributing Italian imports were wheat, barley, and other grains, but also livestock. Wood products were another major carrier of embodied land use in the EU trade market. Regarding the largest product-specific gross land use displacements in the EU shown in Table 4, German imports of wood products led to land use in Poland of 2.4 Mgha, while Swedish land use due to British imports of wood products constituted the second most important flow (2.0 Mgha).

Blue Water Footprints. The most striking net displacements of pressures within the EU were related to blue water consumption. Blue water embodied in Spanish exports dominated completely, with only French exports coming remotely close. The displacement of blue water use to Spain mainly came from consumption in Germany and the United Kingdom; see Table 3. Though the ranking of countries is shifted in the per capita domain in Table 2, Spain still massively dominates with net per capita exports of embodied blue water more than twice those of Luxembourg at second place. The situation is largely explained by the fact that Spain is an important producer of several rather water intensive crops, while at the same time being highly dependent on irrigation due to a semiarid climate.

In the analysis of net blue water exchanges we find that Lithuania had net imports of embodied blue water from all other EU countries, the only such case in our results. Another interesting result is that Portugal's net embodied blue water imports from Spain (277 Mm^3) were considerably larger than its total net imports (235 Mm^3). In fact, despite being a net importer overall, Portugal was a net exporter of embodied blue water to most other EU countries.

Imports of embodied blue water from Spain and France to other EU countries dominate the lists of top country-specific and product-specific displacements of embodied blue water in Tables 3 and 4. In particular, the net German displacement to Spain stands out at 542 Mm^3. The corresponding gross displacement was only slightly larger, and the analysis showed that about 21% of this was related to German imports of oranges, tangerines, and similar fruits. These fruits were also important components in the blue water consumption displaced from the United Kingdom and France to Spain. Another large displacement featured Spain as the importing part: Spanish imports of cereal grains led to 97 Mm^3 of blue water consumption in France, 91 Mm^3 of which were associated with imports of maize (see Table 4).

DISCUSSION

All consumption draws on the finite resources of the planet; however, this fact has become less visible to consumers in industrialized regions such as Europe, as products have become increasingly processed, and consumers are located further from production sites. An inhabitant in a modern city indirectly requires large amounts of land, fresh water, and greenhouse gas emissions to sustain her consumption activities, but she may never see any of these effects first-hand. Through international trade, pressures on the natural system are often located far away from end consumers, and people in urban areas can easily have higher total embodied resource consumption than people living in areas where those resources are abundant.

Input–output analysis has provided important insights into the environmental impacts of consumption,[1,30] which served as the basis for policy such as the EU's Roadmap to a Resource Efficient Europe.[31] The findings of the consumption-based analysis for Europe emphasize the importance of shelter, mobility, and nutrition. Analysis of trade has often focused on aggregate results, addressing questions of responsibility with regard to, primarily, climate change.[9,32] The aggregate results, however, come about through a multitude of interactions in a complex web of global supply chains. A better understanding of cross-country relationships and of the importance of product flows can offer important insights to policy and provide some understanding of economic interests.[33] Analyses can be organized according to product groups, regions,[34] countries,[35] or bilateral trade relationships.[36]

Our analysis addresses the relationships within the EU member states in more detail. On the global level, the accounting for emissions embodied in trade increases the already high carbon footprints of Europe, Japan, South Korea, and the United States.[3,9] The correct accounting for land use displacement increases the land footprint of the same economies which already extract more domestic biomass than less affluent ones.[19] Intra-European trade, however, seems to run in the other direction: heavy polluters or resource users having high *net* emissions embodied in export. Poland and the Czech Republic use a lot of coal for both electricity production and heavy industry, and some of this coal is burnt for producing exports, similar to the role China has in the world economy. Poland and the Nordic countries have a large forestry sector, so that they become net exporters of land due to the export of these products while also using a lot of these products at home. Spain and France have large and productive agricultural sectors, so they export a lot of agricultural products to the UK, Germany, and other European countries. While food production in temperate countries relies mostly on rain-fed agriculture, Spain relies heavily on irrigation, something that can be seen both within its own consumption but also in its net-trade position within the EU.

How can it be that within a global context, we find that high footprint countries have a position as net importer (or displacer), while within Europe, they tend to have a position of a net exporter? To understand the total net position, we need to understand that there is a trade-off between the scale of consumption and the efficiency of production. Affluent countries tend to have a high efficiency, i.e., a lot of value created per unit of resource use or pollution. They also have a high level of consumption. As their exports are lower resource intensity than their imports, they become net importers. Within Europe, however, the differences in consumption are much smaller and less important. Resource intensities differ because of structural and natural differences, not so much due to differences in economic efficiency. Resource-rich countries specialize in resource extraction and processing, whether it is heavy industry (Poland and Czech Republic for coal) or forestry (Finland, Sweden, Poland, Estonia for land) and agriculture (Spain, France for land). The situation for blue water is different. While any biomass production requires water, irrigation is most heavily used in regions where rainfall during the growing season is insufficient to sustain intensive agriculture. In these regions, agriculture easily dominates other water uses.

In its Renewed Sustainable Development Strategy for the EU, the European Council calls for a set of indicators for sustainable development at the "appropriate level of detail" to ensure sufficient coverage of the complex environmental challenges facing society.[37,38] The heterogeneity displayed by our results supports the notion that sustainability analyses need to simultaneously assess more than one dimension of the environmental sustainability challenge. Even within a single economic region like the EU, footprint profiles vary considerably between countries. However, more research is still needed to improve models and increase our understanding of how environmental pressures are displaced globally. First, macro level input–output models like ours generally carry significant uncertainties, and second, defining indicators to represent complex environmental issues inevitably involves some subjective choices. This is especially true for land and water use accounting. For instance, although the EF is widely used, another well recognized approach to the same environmental challenge instead attempts to measure the human appropriation of net primary productivity (HANPP)—see refs 39 and 40 for discussions of these two approaches. The issue of water use accounting is perhaps even more debated, referring to the water types distinguished in the introduction. Furthermore, the environmental impacts of land and water use very much

dx.doi.org/10.1021/es301949t | Environ. Sci. Technol. 2012, 46, 10883−10891

depend on where and when the water and land use take place. The reader is referred to the SI for a further discussion of these issues.

Finally, although the focus of this study has been the displacements of environmental pressures through trade, it should be pointed out that such displacements are not problematic in themselves, but may in fact carry environmental benefits.[41] Different regions have different comparative advantages in terms of production technologies and natural endowments, and international trade can serve to optimize the global society's overall use of natural resources.[42,43] The potential negative impacts depend on local conditions; hence European displacements of forest land use to Finland, where forest stocks are large and increasing,[44] should represent less of a concern than displacements of blue water consumption to Spain, where water resources are under pressure.[45]

■ ASSOCIATED CONTENT

Supporting Information

Further explanation of the extended MRIO model and the footprint indicators; discussion of validity and limitations; complete lists of regions and sectors included in the MRIO model, and countries and primary products included in the physical system; extensive footprint results including detailed displacements between all 27 EU countries; results for the complete EF and WF indicators. This information is available free of charge via the Internet at http://pubs.acs.org. A version of the model can be accessed at www.eureapa.net.

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Notes

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The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The EE-MRIO model used for this analysis was constructed as part of the "One Planet Economy Network: EU" (OPEN:EU) project funded by the European Commission's 7th Framework Programme (Grant 227065). TOC art was created using Circos.[46] We thank the reviewers for their helpful comments.

■ REFERENCES

(1) Tukker, A.; Jansen, B. Environment impacts of products - A detailed review of studies. *J. Ind. Ecol.* **2006**, *10* (3), 159−182.

(2) Galli, A.; Wiedmann, T.; Ercin, E.; Knoblauch, D.; Ewing, B.; Giljum, S. Integrating Ecological, Carbon and Water footprint into a "Footprint Family" of indicators: Definition and role in tracking human pressure on the planet. *Ecol. Indic.* **2012**, *16*, 100−112.

(3) Hertwich, E. G.; Peters, G. P. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environ. Sci. Technol.* **2009**, *43* (16), 6414−6420.

(4) Galli, A.; Kitzes, J.; Wermer, P.; Wackernagel, M.; Niccolucci, V.; Tiezzi, E. An exploration of the mathematics behind the Ecological Footprint concept. *Int. J. Ecodyn.* **2007**, *2* (4), 250−257.

(5) Mekonnen, M. M.; Hoekstra, A. Y. A global assessment of the green, blue and grey water footprint of crops and crop products. In *Value of Water Research Report Series*; UNESCO-IHE: Delft, the Netherlands, 2010.

(6) Ewing, B.; Moore, D.; Goldfinger, S.; Oursler, A.; Reed, A.; Wackernagel, M. *Ecological Footprint Atlas 2010*; Global Footprint Network: Oakland, 2010.

(7) Hoekstra, A. Y.; Mekonnen, M. M. The water footprint of humanity. *Proc. Natl. Acad. Sci. U.S.A.* **2012**, *109* (9), 3232−3237.

(8) Peters, G. P.; Marland, G.; Le Quere, C.; Boden, T.; Canadell, J. G.; Raupach, M. R. Rapid growth in CO_2 emissions after the 2008−2009 global financial crisis. *Nat. Clim. Change* **2012**, *2* (1), 2−4.

(9) Peters, G. P.; Minx, J. C.; Weber, C. L.; Edenhofer, O. Growth in emission transfers via international trade from 1990 to 2008. *Proc. Natl. Acad. Sci. U.S.A.* **2011**, *108* (21), 8903−8908.

(10) Carbon Footprint of Nations - Emissions Worldwide. http://carbonfootprintofnations.com/ranking.php.

(11) Lenzen, M.; Murray, S. A. A Modified Ecological Footprint Method and its Application to Australia. *Ecol. Econ.* **2001**, *37* (2), 229−255.

(12) Wiedmann, T.; Minx, J.; Barrett, J.; Wackernagel, M. Allocating ecological footprints to final consumption categories with input-output analysis. *Ecol. Econ.* **2006**, *56* (1), 28−48.

(13) McDonald, G. W.; Patterson, M. G. Ecological Footprints and interdependencies of New Zealand regions. *Ecol. Econ.* **2004**, *50* (1−2), 49−67.

(14) Feng, K.; Chapagain, A.; Suh, S.; Pfister, S.; Hubacek, K. Comparison of Bottom-Up and Top-Down Approaches to Calculating the Water Footprints of Nations. *Econ. Syst. Res.* **2011**, *23* (4), 371−385.

(15) Guan, D.; Hubacek, K. Assessment of Regional Trade and Virtual Water Flows in China. *Ecol. Econ.* **2007**, *61* (1), 159−170.

(16) Yu, Y.; Hubacek, K.; Feng, K.; Guan, D. Assessing regional and global water footprints for the UK. *Ecol. Econ.* **2010**, *69* (5), 1140−1147.

(17) Schoer, K.; Weinzettel, J.; Kovanda, J.; Giegrich, J.; Lauwigi, C. Raw Material Consumption of the European Union − Concept, Calculation Method, and Results. *Environ. Sci. Technol.* **2012**, *46* (16), 8903−8909.

(18) Weinzettel, J.; Steen-Olsen, K.; Galli, A.; Cranston, G.; Ercin, A. E.; Hawkins, T.; Wiedmann, T.; Hertwich, E. *Footprint Family Technical Report: Integration into MRIO Model*; Feb 7, 2011.

(19) Weinzettel, J.; Hertwich, E. G.; Peters, G. P.; Steen-Olsen, K.; Galli, A. Affluence drives the globalization of land use. Submitted for publication.

(20) Ridoutt, B. G.; Pfister, S. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Global Environ. Change* **2010**, *20* (1), 113−120.

(21) Smeets, E.; Weterings, R. *Environmental Indicators: Typology and Overview; 25*; European Environment Agency, 1999.

(22) Meyfroidt, P.; Lambin, E. F. Forest transition in Vietnam and displacement of deforestation abroad. *Proc. Natl. Acad. Sci. U.S.A.* **2009**, *106* (38), 16139−16144.

(23) Peters, G. P.; Hertwich, E. G. CO_2 Embodied in International Trade with Implications for Global Climate Policy. *Environ. Sci. Technol.* **2008**, *42* (5), 1401−1407.

(24) Narayanan, G. B.; Walmsley, T. L. *Global Trade, Assistance, and Production: The GTAP 7 Data Base*; Center for Global Trade Analysis, Purdue University: West Lafayette, IN, 2008.

(25) Peters, G. P.; Andrew, R.; Lennox, J. Constructing an environmentally extended multi-regional input-output table using the GTAP database. *Econ. Syst. Res.* **2011**, *23* (2), 131−152.

(26) Haberl, H.; Erb, K. H.; Krausmann, F.; Gaube, V.; Bondeau, A.; Plutzar, C.; Gingrich, S.; Lucht, W.; Fischer-Kowalski, M. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *Proc. Natl. Acad. Sci. U.S.A.* **2007**, *104* (31), 12942−12947.

(27) Ewing, B. R.; Hawkins, T. R.; Wiedmann, T. O.; Galli, A.; Ercin, A. E.; Weinzettel, J.; Steen-Olsen, K. Integrating ecological and water footprint accounting in a multi-regional input−output framework. *Ecol. Indic.* **2012**, *23*, 1−8.

(28) FAO. FAOSTAT Database; http://faostat.fao.org/; accessed June 2010.

(29) Meyfroidt, P.; Rudel, T. K.; Lambin, E. F. Forest transitions, trade, and the global displacement of land use. *Proc. Natl. Acad. Sci. U.S.A.* **2010**, *107* (49), 20917−20922.

(30) Hertwich, E. G. The life cycle environmental impacts of consumption. *Econ. Syst. Res.* **2011**, *23* (1), 27−47.

(31) *Analysis Associated with the Roadmap to a Resource Efficient Europe, Part II*; European Commission: Brussels, 2011.

(32) Peters, G. P.; Hertwich, E. G. Post-Kyoto greenhouse gas inventories: Production versus consumption. *Clim. Change* **2008**, *86*, 51−66.

(33) Xu, M.; Li, R.; Crittenden, J. C.; Chen, Y. CO_2 emissions embodied in China's exports from 2002 to 2008: A structural decomposition analysis. *Energy Policy* **2011**, *39* (11), 7381−7388.

(34) Wiebe, K. S.; Bruckner, M.; Giljum, S.; Lutz, C.; Polzin, C. Carbon and Materials Embodied in the International Trade of Emerging Economies. *J. Ind. Ecol.* **2012**, *16* (4), 636−646.

(35) Weber, C.; Matthews, H. S. Embodied Environmental Emissions in U.S. International Trade, 1997−2004. *Environ. Sci. Technol.* **2007**, *41* (14), 4875−4881.

(36) Xu, M.; Allenby, B.; Chen, W. Q. Energy and Air Emissions Embodied in China-US Trade: Eastbound Assessment Using Adjusted Bilateral Trade Data. *Environ. Sci. Technol.* **2009**, *43* (9), 3378−3384.

(37) *Renewed EU Sustainable Development Strategy*; 10917/06; European Council: Brussels, June 26, 2006.

(38) Adelle, C.; Pallemaerts, M. *Sustainable Development Indicators. An Overview of Relevant Framework Programme Funded Research and Identification of Further Needs in View of EU and International Activities*; European Commission, 2009.

(39) Haberl, H.; Wackernagel, M.; Krausmann, F.; Erb, K. H.; Monfreda, C. Ecological footprints and human appropriation of net primary production: A comparison. *Land Use Policy* **2004**, *21* (3), 279−288.

(40) Vačkář, D. Ecological Footprint, environmental performance and biodiversity: A cross-national comparison. *Ecol. Indic.s* **2012**, *16*, 40−46.

(41) Peters, G. P.; Hertwich, E. G. Trading Kyoto. *Nat. Rep. Clim. Change* **2008**, *2* (4), 40−41.

(42) Ayres, R. U. Commentary on the utility of the ecological footprint concept. *Ecol. Econ.* **2000**, *32* (3), 347−349.

(43) Dalin, C.; Konar, M.; Hanasaki, N.; Rinaldo, A.; Rodriguez-Iturbe, I. Evolution of the global virtual water trade network. *Proc. Natl. Acad. Sci. U.S.A.* **2012**, *109* (16), 5989−5994.

(44) Liski, J.; Lehtonen, A.; Palosuo, T.; Peltoniemi, M.; Eggers, T.; Muukkonen, P.; Mäkipää, R. Carbon accumulation in Finland's forests 1922−2004 − an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. *Ann. For. Sci.* **2006**, *63* (7), 687−697.

(45) Pfister, S.; Koehler, A.; Hellweg, S. Assessing the Environmental Impacts of Freshwater Consumption in LCA. *Environ. Sci. Technol.* **2009**, *43* (11), 4098−4104.

(46) Krzywinski, M. I.; Schein, J. E.; Birol, I.; Connors, J.; Gascoyne, R.; Horsman, D.; Jones, S. J.; Marra, M. A. Circos: An information aesthetic for comparative genomics. *Genome Res.* **2009**, *19*, 1639−1645.