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Material Hide-and-Seek: Looking for the Resource Savings Due to International Trade of Food Products

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Key Points:

- International trade of food products reduced the rise of material footprint in our sample on a global scale
- A trade-off between material efficiency improvement and material stock accumulation is detected
- Domestic efficiency improvements tend to substitute for food imports

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Adverse environmental effects of international trade are emphasized in the literature frequently. Nevertheless, following a theoretical trade logic, the production of goods in regions with higher resource efficiency may lead to reduced global resource use. In this article, major drivers of food-related material footprint (MF) are analyzed at the global, regional, and country levels. Changes in consumption, the supply chain's efficiency, and participation in international trade are considered drivers of MF. An index decomposition analysis was conducted to assess the contribution of these factors to the variation of the MF in time. Our results partially prove that the optimization regarding natural resource use may contribute to a lower MF of food consumption. Regions and countries with increasing food imports reinforce their efficiency improvement with the lower resource intensity of imported goods, and the international trade counteracted the effects on additional resource requirements of increasing consumption throughout the analyzed period (1990–2013). Furthermore, the impact of international trade on capital stock is discussed. In line with the descending flow-type material intensity by approximately 5%, the material composition of the footprint has shifted toward stock building materials. Additionally, the intensity of the trade was found to be negatively correlated with domestic efficiency improvements.

Plain Language Summary Although serious resource needs and pollutions associate the international trade, it is suspected to play an essential role in the more effective distribution of natural resources (e.g., land, water, energy). In this article, significant drivers of food-related material footprint (MF) are analyzed globally, at regional and country levels. Changes in consumption, the supply chain's efficiency, and participation in international trade are considered to form food products' overall resource requirements. Our results partially prove that the optimization regarding natural resource use may contribute to a lower MF of food consumption. Increasing food imports reinforces efficiency improvement with the lower resource needs of imported goods. The international trade counteracted the effects on additional resource requirements of increasing consumption throughout the analyzed period (1990–2013). It was also described that the more effective the food system becomes, the more resources are used to build up its infrastructure.

1. Introduction

The contribution of food consumption to the environmental impacts of society is essential. Food system is responsible for one-third of the global greenhouse gas emissions (GHG), depending on the scope of the analysis (Garnett, 2011; Poore & Nemecek, 2018). Food production evokes 32% of the terrestrial acidification and 78% of the eutrophication worldwide (Poore & Nemecek, 2018). In the meanwhile, the resource demand induced by the global food supply chains is remarkable as well. Alexander et al. (2019) emphasize that agricultural production indicates 38% of global land use; furthermore, a permanent rise in this ratio is foreseen as multiple driving factors present. Also, at least 70% of the global freshwater resources is utilized in food systems (Teisl, 2011). Nutrition required 21.3 gigatones of raw materials, that is, 21% of the natural resources entering the socio-economic system at global scale (de Wit et al., 2020).

The recent decade has witnessed increasing debates worldwide on international trade. Social and economic effects are emphasized from the political point of view; however, the scientific lens of academia and international organizations highlights environmental issues as well. Global exports doubled in terms of physical volumes of materials (UN IRP Global Material Flows Database), while its corresponding monetary value increased by 220% (WTO Database) between 1995 and 2015. Growth in food exports exceeded 90% (FAO). The material basis of the trade, however, exceeds the amount of the traded goods significantly (Wiedmann et al., 2015).

Interpretation of the role of international trade in the sustainable pathway of our future development is controversial. On the one hand, there is a clear awareness on the adverse environmental impacts of the trade itself, as it requires additional resource inputs (Beylot et al., 2019; Long et al., 2018; Sandström et al., 2018; Wiedmann & Lenzen, 2018). The intensifying international trade was detected as one of the main barriers of decoupling in a recent systematic review by Helmut Haberl et al. (2020).

On the other hand, however, production of goods in countries characterized by higher resource efficiency may lead to lower global resource use, theoretically (Bruckner et al., 2012; Plank et al., 2018). Literature has shown little evidence on the latter feature of international trade. For instance, Schaffartzik et al. (2013) present increasing net imports in line with stagnating row material consumption (RMC) in Austria between 1995 and 2007. De Boer et al. (2019) found that optimizing sources of imports could result in significantly lower environmental impacts of consumption.

The explanation of paradox above is twofold. First, the measurement usually refers to actual consumption. It will reveal distinct amount of embodied environmental impact in trade inevitably; nevertheless, production and distribution of the same set of goods domestically may accompany even higher emission and resource requirements (Engelhaupt, 2008; Nemecek et al., 2016; Teisl, 2011). Second, international trade and economic growth go hand-in-hand; increased impacts and resource needs may be driven not by the trade exclusively, but the emerging affluence of the society, which allows purchasing more goods and services generally. A recent study of Barbara Plank et al. (2018) have resolved the problem of the latter bias for aggregated resource use. They found that 30% of RMC growth is associated with the international trade globally between 1990 and 2010. Wood et al. (2020) found that energy efficiency improvement has counteracted the effect of trade growth, and trade is responsible for approximately 15% of the positive drivers of GHG emissions.

The preceding assessments have targeted the environmental impacts or overall resource use generaly. Nevertheless, food provision is a specific one among the different supply chains, since it relies on natural conditions significantly. Zhao et al. (2019) have found that 35% of the food-related GHG emissions were embodied in trade, in the same time, since natural resources are unevenly distributed among countries and regions, in theory, international trade should have optimized resource allocation through outsourcing domestic production of food commodities to the countries characterized by higher efficiency (Dalin & Rodriguez-Itube, 2016; Zhao et al., 2019). It is referred to as the theory of comparative advantages in economics. With regard to biomass production, such comparative advantages can also be achieved by wealthier natural resource endowment. A cross-country analysis by MacDonald et al. (2015) delivers some evidence on this phenomenon. Roux et al. (2021) analyzed the effect of the agricultural product's consumption and trade on human appropriation of net primary production (HANPP) with a novel decomposition index. They found that international trade contributed to the anthropogenic pressure on the ecosystems moderately last decades.

In the sustainability literature, this very concept is also formulated as "resource savings." The virtual water trade, for instance, has been proven to be more effective in water resources allocation through exchange between regions with different water productivity of crops (e.g., Dalin et al., 2012; X. Liu et al., 2019). Fader et al. (2011) found that 3.5% of water and 5% of land were saved due to international trade when compared to the self-sufficient production globally. Inasmuch as previous analyses isolated the gains of optimized resource use due to the trade from socio-economic processes, our study attempts to address the issue of resource savings in a broader context, as Wang et al. (2019) proposed. Therefore, we quantified the effect of consumption patterns, demographics, and affluence on resource use, and discussed its social and ecological consequences.

Contrary to the findings presented above, Kastner et al. (2014) suggested that advance in farm management and technology could be a more effective way to improve the overall productivity, whereas they did not consider the costs of such investments. Sandström et al. (2018) provide a regression model on CO_2 emissions of food consumption regarding European countries. They report the emissions outsourced outside the EU to reinforce the overall emissions; however, the model fit is rather weak, and the multicollinearity is not reported. Schaffartzik et al. (2019) provide a comprehensive criticism of the theory of comparative advantages.

Despite the quasi clear interpretation of the adverse environmental effects evoked by the use of the natural resources during the international trade at the aggregate level, a few cases do support the theory of its effective influence on resource allocation. It would be reasonable to hypothesize that each type of economic activity is associated with different respond through globalization, thus calling for different policy interventions, as it was suggested recently be (Wood et al., 2020). Product flows of extractive sectors, allocating non-renewable natural resources; manufacturing industries; and services with hardly any flow-type resource requirement might diverge in their influences on income, employment, inequality effect, and environmental pressure. Food supply is unique as well in a sense, that utilization of renewable energy sources is even determinant for production in many cases. One may assume, that material and emission productivity of extractive sectors (mining, agriculture, and tourism) vary intensely worldwide, in contrast to production and services.

Although studies have usually decomposed the changes in water and land resources or ecosystem functions, none has, to our knowledge, use the material footprint (MF) of food consumption as an indicator of pressure on the environment. Is it possible, that international trade reduces the resource use in several globalized supply chains, whereas in others the trade reinforces the unsustainable trends? Is food consumption optimal as globalized in this regard? Our aim was to explore whether natural resource savings due to international trade are present at different scales in the socio-economic system. We intend to describe and reveal the multiple effects of the international trade in line with the long-term process of economic development and resource efficiency progress.

In this article, drivers of food-related MF are analyzed at the global, regional, and country level. Changes in consumption, efficiency of the supply chain, and participation in the international trade are considered as drivers of the MF. In order to assess the contribution of the factors to the variation of the MF in time, we conducted an index decomposition analysis (IDA) on data reporting the MF and food consumption globally, as well as four world regions, and seven countries of different socio-economic conditions. Furthermore, the influence of the international trade on the productive infrastructure at the country level is examined as well; since material stock accumulation is recognized as a fundamental constraint of the decoupling of the natural resource use from the economic growth recently. Additionally, the social impact of international trade among the food supply chain are addressed, along with further research directions.

2. Materials and Methods

In this section, methodology and data sources are introduced. Details with regard to MF assessment (Section 2.1), the decomposition analysis (Section 2.2) are provided, followed by the spatial levels covered during the analysis (Section 2.3) and the description of the databases (Section 2.4).

2.1. Material Footprinting of Food Trade

The physical amount of domestic extraction (DE) and import are intensely used indicators in socio-economic metabolism studies; additionally, they are reported worldwide by statistical offices and several institutions in four groups of materials, namely biomass, non-metallic minerals, metal ores, and fossil fuels. Biomass extraction refers to primary phytomass, and wild animals, ferrous and non-ferrous ores are raw materials entering the industry, while non-metallic minerals consist mainly of construction materials. The MF cumulates all the materials extracted and processed to satisfy a product's or service's particular final use. For instance, the MF comprises entirely the feed, heat energy sources, transportation fuels, and metal content of the equipment required to produce meat consumed in the households.

We processed two environmentally extended multi-regional input-output tables (MRIOT) to explore MF of the food consumption, namely the EXIOBASE v3.2 and the Eora26. In order to disaggregate the factors

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of changes of MF in time at the global and regional level, the Eora26 was utilized due to its data delivered at constant prices. Eora26 was also used to assess the capital stock of the food supply chain (Section 3.4). It report the non-metallic minerals as construction minerals, so fertilizers were excluded. The mass of fertilizers, though, is negligible in comparison to other minerals in the food MF. Significantly higher food commodity resolution of the EXIOBASE was called to illustrate the characteristics of emerging, transiting or industrialized countries by seven sample countries. Both MRIOTs were processed using the calculation of the Leontief-inverse toward the extraction of direct and indirect environmental impacts (see Supporting Information for details).

2.2. Decomposition Analysis

Decomposition analysis was used to assess the contribution of international trade to the variation of the MF. In brief, decomposition analysis dedicates the change of an aggregate to several predefined factors. Two basic ways of decomposition exist; structural decomposition analysis (SDA) and IDA (Su & Ang, 2012). We applied the Logarithmic Mean Divisia Index (LMDI) type of IDA, hence it is symmetric, and the calculation does not produce residuals (Ang, 2005). Decomposition analyses were primarily utilized in energy studies, followed by numerous applications in socio-economic metabolism research as well (Plank et al., 2018; IRP, 2019; Q. Liu et al., 2019; Wenzlik et al., 2015; Wood, 2009; Wood et al., 2020).

In our study, the aggregate is the MF; the sum of the MF of three food-related products of the EORA26, namely agriculture, fishing, and food & beverages as sub-categories (Equation 1). More than 70 food commodities of FAO food balance sheets (FBS) were aggregated into these sub-categories, to construct the group of primary products (agriculture), wild catches and aquaculture (fishing), as well as processed food (food & beverages). The latter category involves all the animal products as well (Data harmonization, see the Supporting Information). Additive form of calculation was used (Equation 2), due to its easier interpretation.

$$\mathrm{MF} = \sum_{i,j} \mathrm{MF}_{ij} = \sum_{i,j} C \frac{C_i}{C} \frac{C_{ij}}{C_i} \frac{\mathrm{MF}_{ij}}{C_{ij}} = \sum_{i,j} C\, S\, T\, I \tag{1}$$

$$\Delta\mathrm{MF} = \mathrm{MF}^t - \mathrm{MF}^0 = \Delta\mathrm{MF}_C + \Delta\mathrm{MF}_S + \Delta\mathrm{MF}_T + \Delta\mathrm{MF}_I \tag{2}$$

where MF_{ij} is the MF of food product category i form origin j (domestic or imported); C is the volume of total consumption (referred to as "Consumption", briefly); C_i is the consumption of the food product category i; C_{ij} is the consumption of food product category i form origin j (domestic or imported); S is the structure of food consumption (Structure); T is the origin of the food consumption (Trade); I is material intensity of production (Intensity). C, S, T, and I are the factors of the decomposition analysis.

2.3. Spatial Resolution of the Analysis

In order to analyze the contribution of the international trade to the changes in food MF, we involved three spatial levels. At global level, our data set consists of data regarding 189 countries. Food consumption, production recipes, and involvement in the international trade varies regionally for high extent. FAO provides 34 overlapping country groups along with its country-level data. We present here four world regions with diverse historical and socio-economic background, namely Central and South Asia (CSA), which involves India; Eastern Europe and Russia (EER); Middle Africa (MA); and Western Europe (WE) to illustrate how trade patterns affect the MF of food consumption.

The country-level assessment was performed on seven countries, which are classified on their production and trade patterns in material dimensions as following. Self-sufficient and net-exporter countries are Brazil (BR), and Poland (PL); self-sufficient, but importers are Denmark (DK), Hungary (HU), and Turkey (TR); while not self-sufficient countries are China (CN) and Portugal (PT). It is worth to state, that while PT has to import a significant amount of both plant and animal products, self-sufficiency of CN fails in cases of product groups consumed in limited amounts, that is, dairy products, cattle, and other meat.

Note, that self-sufficiency and importer status at the same time is not a paradox. Hence they might refer to different specific products. Intensification of imports does not erode self-sufficiency (O'Dorico et al., 2014). Also, significant exports of these countries are observed in several commodity groups, for instance, cereals in HU. Nevertheless, this study focuses on imports, and the hypothesis is that imported goods can lessen resource use. In the case of self-sufficient and net exporter countries, none of the food commodity groups has a negative trade balance, in contrast to others. Import, though, may occur in all product groups.

2.4. Data Treatment

Eora26 covers years 1990–2015, EXIOBASE v3.2 is provided for period 1995–2015, while FAO FBS data are updated until 2013 when this manuscript was written. Annual, short-term changes were provided in "smoothed" version, a moving average-like calculation to avoid random effects of climatic conditions. In this case, 0 refers to t-y in Equation 2, where y is the number of years covered. Moving averages were tested for y to be 2, 3, 4, and 5.

FAO provides data on domestic food supply, that is, production less exports and stock variation, plus imports. Nevertheless, it has two significant shortcomings. First, re-exports are considered in imported amount, which obviously does not support domestic nutritional purposes. Food re-exports were estimated by 8%, globally (MacDonald et al., 2015). Second, the "stock variation" is actually consumption/storage of natural resources extracted in a different time period. If it would be considered, the MF in a given year would not meet the amount of the materials required for final use purposes in that year. In smaller countries, for instance, amount of utilization from stocks of cereals or fruits may even exceed the volume produced that year. Consequently, final consumption was split with regard to origin as consumption less import equals the domestic supply; and import, respectively.

In few cases, it produced negative values, which was substituted either with very low values, near to zero, or with a value keeping the MF_{ij} per consumption ratio constant. Furthermore, the FBS contains bulk data, thus we considered only the amount for human nutritional purposes in case of import. To maintain data consistency, this food ratio was applied to MF as well, to exclude resource use supporting feed and fodder production. The MF of food consumption was disaggregated into domestic and imported part as well. In this way, calculation of intensity of imported food and of domestic origin is now possible.

The material stock of embodied capital in the Hungarian food supply chain was estimated by the production function of distinct sub-sectors and their net addition to stock (NAS), calculated as the MF of the gross fixed capital formation (GFCF) less depreciated capital stock and fossil fuel content of the footprint (for methodological details see Dombi, 2019).

3. Results and Discussion

Section 3.1 provides results of the decomposition analysis at the global level, followed by regional and country-specific results in Sections 3.2 and 3.3. The next part deals with interactions of the trade and the capital stock (Section 3.4), as well as other environmental impacts of trade and social frictions (Section 3.5).

3.1. The Role of Food Trade at Global Scale

Global food consumption rose by 70% between 1990 and 2013, while the MF of the consumption of food commodities exceeded 60%. The share of imported food increased moderately during the indicated period. As Table 1 reports, therefore, the permanent ascending trend of food consumption has not been translated into an emerging MF with the same pace. We applied decomposition analysis to assess the role of the consumption volume and structure, the trade patterns, and the technological progress in this very path of emerging food supply.

Figure 1 displays the main trends in decomposition by data from the FAO FBS and Eora26 (constant prices). This variation is explained by the four factors, in the way that they sum up exactly to the variation of MF. The light blue bars represent the absolute values of the MF, while four additive bars on the right side of each MF bar indicate the factors enhancing (brown) or restraining (green) its growth. Generally, the declining

Table 1
Trends of Food Consumption and Its Material Footprint at Global Scale

	Total food consumption (kt)	Import share	Processed food ratio	Material footprint (kt)	Import share	Processed food ratio
1990	2,402,467	0.245	0.149	10,229,448	0.091	0.614
1995	2,729,355	0.249	0.146	12,198,188	0.097	0.608
2000	3,145,265	0.254	0.143	13,527,879	0.108	0.595
2005	3,445,026	0.276	0.146	14,955,784	0.116	0.598
2010	3,834,883	0.300	0.148	16,513,189	0.113	0.596
2013	4,079,122	0.318	0.147	16,518,208	0.115	0.593
Change over 1900–2013 (%)	70	29	−2	61	26	−3

intensity (i.e., increasing material efficiency), and the emerging role of imported commodities were able to counteract the increasing demand for food last decades.

Considering two-year periods chained decomposition presented in Figure 2, that is, the reference year is *t-2*, so the year before the previous year; the variation of the MF (indicated with cyanic blue in the figure) is merely within the range of 10% (19 out of 22 observations), while 45% of the observations range between 5% and 10%. The international trade reinforced the growing MF in two years out of 22 exclusively; unfortunately, the intensity has contributed the MF growth through 12 observations on a two-year basis. Even consumption structure shows less, that is, 10 periods of "pulling up" the MF of food consumption. The material intensity of imported food commodities has dropped by 8%, while domestic material intensity was almost 3% higher in 2013 than in 1990. As the majority of food commodities globally (70%) comes still from the inland supply, the intensity has been controversial with regard to MF for long time periods according to the results of the decomposition analysis (2003–2009), as it reinforced the MF growth. Furthermore, the material intensity of domestic supply is by 260% higher than that of imported commodities; 5.3 t/t and 1.5 t/t, in particular. It is due to the structure of imports. Hence three-fourth of imported goods are vegetal products–although this ratio is rapidly changing toward a higher share of processed food, imports constitute moderate part of total food MF, 9% in 1990% and 12% in 2013. Meanwhile, most animal products are produced inland with high material intensity.

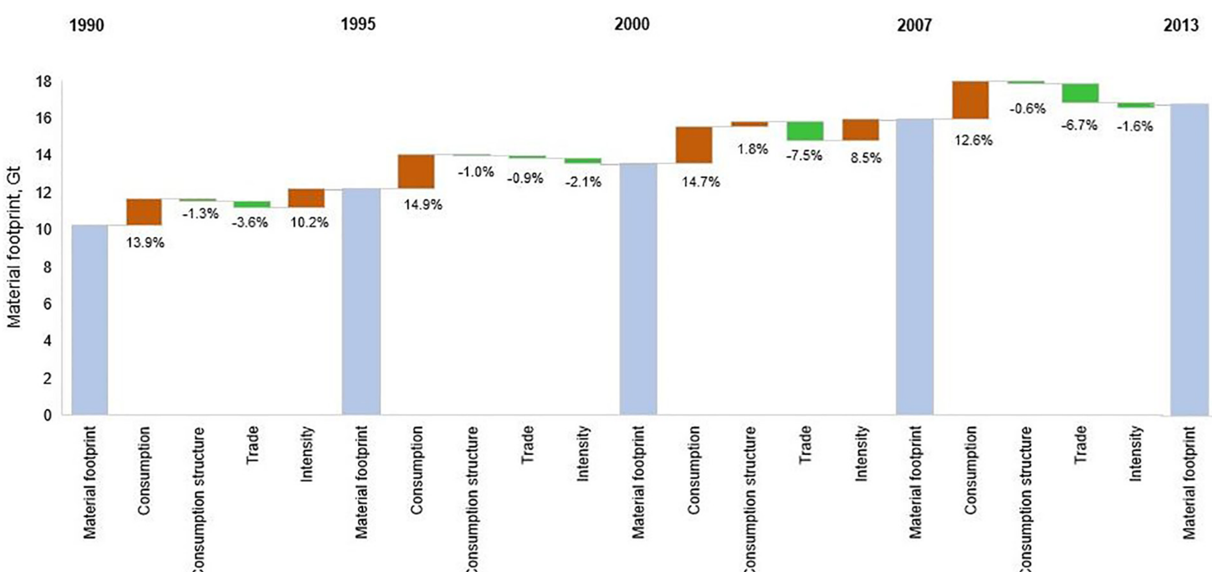

Figure 1. Decomposition of food-related material footprint at global scale (kt).

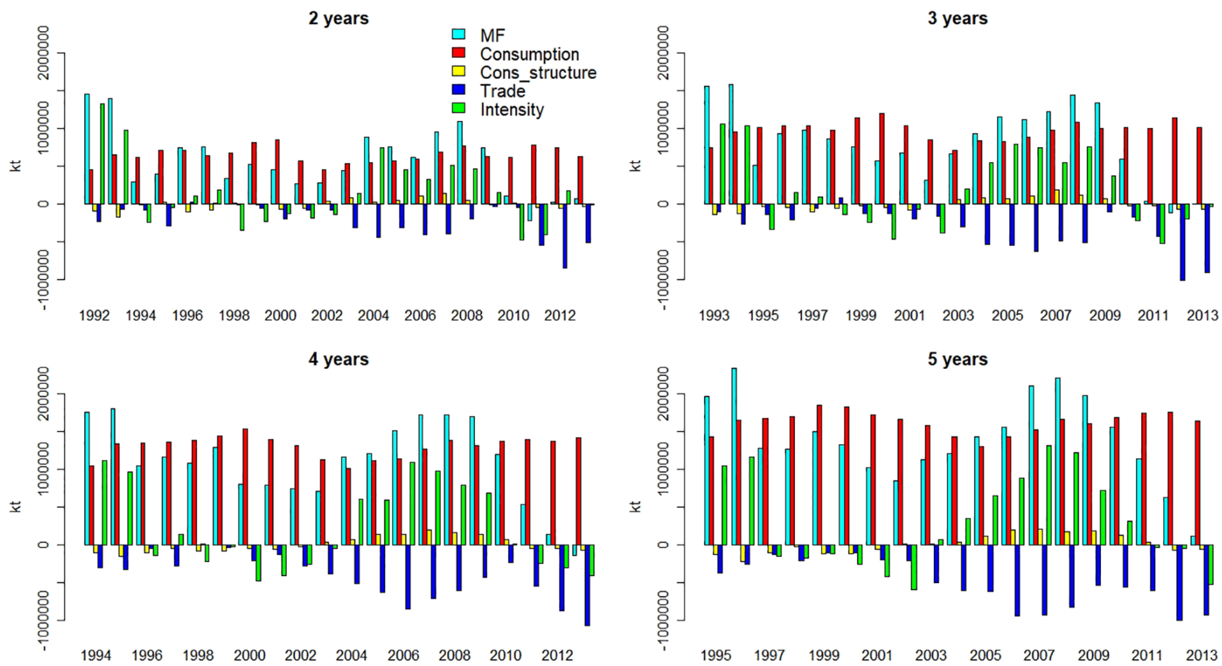

Figure 2. Results of the decomposition analysis by applying different moving averages.

Hence consumption volume (red bars in Figure 2) exceeds the contribution of the structure significantly, one could conclude that the size of the population is the primary driver of food consumption's resource use. Societies with intensive population growth accompany limited changes in consumption structure, as regional and country-level assessment in Sections 3.2 and 3.3 will report. Global food supply grew by 50% in 1995–2013 according to FAO statistical database. The protein content of the nutrients emerged moderately, by 12% in this period. In the same time, the population growth performs as 24%. Thus, the energy intake was improved; however, the improvement is still not protein-based.

Studies by Alexander et al. (2015) and Roux et al. (2021) report more robust structural effects of dietary changes. Unlike in those assessments, the decomposition in this study does not account for the population directly. Instead, the total consumption of food products and the ratio of particular commodities in consumption are considered. In other words, increasing per capita consumption of a food product is considered a dietary change according to those methods. Simultaneously, it appears among structural changes in our study only if this change resulted in an altered share of food products in the customer basket. Therefore, this study's consumption factor overlap some of the structural effects in the sense of the above-referred analyses, as it is presented in Figure S1. This conceptual difference, however, does not affect the decomposition results concerning the intensity and the international trade.

The reasons for relatively moderate ascend in natural resource use of food consumption are multiple (34%, see Table 1). First, the efficiency gains are significant; the intensity is lower by 11% of MF in 2013. Second, international trade delivers optimized resource allocation to some extent, as it was discussed above. The most intensive process in two analyzed decades was the expansion of the global food supply chain. 50% increment in food supply was supported by 35% higher domestic supply and 92% higher amount of global exports. Finally, the growth of the supply of more protein-rich animal products is moderate compared to the total food supply and population growth. Therefore, the growth of resource needs and food consumption is reinforced by modest structural effect.

As Figure 2 reports, the trends and the structure of the decomposition results remain stable under any length of the chosen period. Prolonging the smoothed period by moving averages of chained decomposition results in higher volume and volatility in MF changes, obviously. In the remainder part of the article, we refer to the two-year smoothed chained decomposition, as it controls for random variation in natural conditions without a risk of overlooking a long-term trend during the analysis.

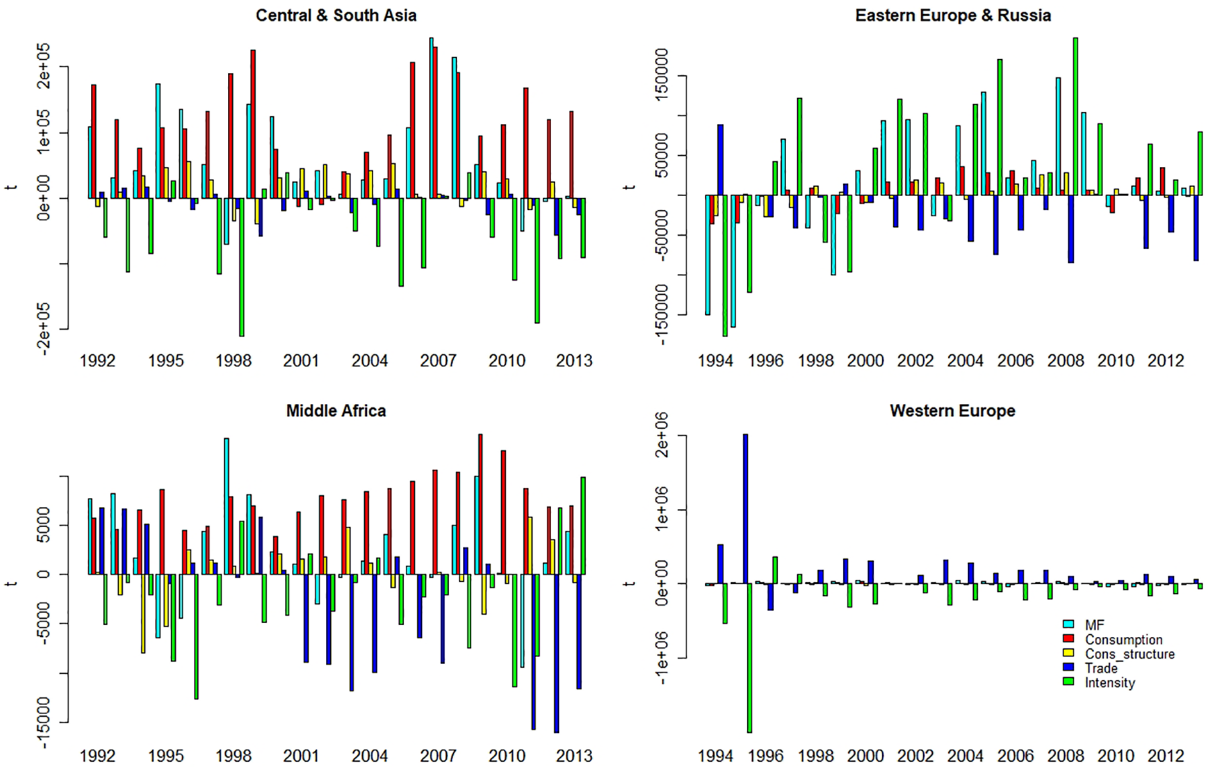

Figure 3. Decomposition analysis of four analyzed regions (t).

3.2. Regional Characteristics

Variation of MF addresses the analyzed factors by significant differences, as Figure 3 reports. Two regions out of four are characterized by consumption volume as a major driver of the food MF (CSA and MA). Structural factor plays a minor role in all of the regions according to our concept of the consumption structure, while resource efficiency shows a wide range of effects.

CSA covers 14% of global food-related MF and 19% of food consumption. This region is self-sufficient with regard to food products, the share of imports in consumption is below 7%. The structure of consumption is rather stable, the share of products from the food industry sector, containing animal products as well, increased from 8% to 10% during the analyzed period. In contrast, the population has grown by 46%, and food consumption has almost doubled (84%). Majority of effects reducing the increment in MF accompany the efficiency gains; especially those of domestic food supply. The domestic material intensity dropped by 26%, and it was one-third of the global average in 2013; 3.4 t/t in contrast to 5.2 t/t.

EER is responsible for 5% of demand for food, and 6% of related MF at global scale. It is the only region in the sample characterized by descending population (−25%). Consumption volume and structure, as well as the share of imported and processed food, do stagnate. The ratio of imported food commodities reached the lowest level in 1994–1998, followed by a rapid and permanent increment from 20% to 35% in 2013. The financial crisis in 2008–2009 hit the EER region intensely, resulted in a short drop in imports, which is illustrated by our two-year smoothed chained decomposition perfectly; two years after the crisis (2009 and 2010) witness the trade slight reinforcing the growth of the food-related MF.

Middle African region illustrates perhaps the most interesting case among the analyzed world regions. The variation of the MF is relatively low and stable, the population has doubled, and the food consumption has risen by 148%. In contrast, the food MF is higher by 32%, which is remarkably lower growth with regard to population and food supply. The moderate MF increment is a result of unattached consumption structure, on the one hand, the efficiency gains, and the increasing imports. The former factor is rather originated in threats related to malnutrition; however, there are notable efficiency improvements present in the MA region's food system. The material intensity of the domestic food supply was by 40% lower in 2013 than in 1990. Furthermore, its level is 70% of the global intensity. The improvement in imported commodities is even more robust, that is, 55%. With particular regard to the international trade, the region shared the path with EER regions, in the sense of trend shifting at the same point in time. In the new Millennia, import share turned into an ascendance after years of decreasing. In the same time, the material intensity of imported food commodities has dropped by nearly 70%. Furthermore, similarly to the EER region, the short-term effect of the financial crisis is experienced by the region.

WE is a net importer of food commodities. Data regarding WE region, though are harmed by intensive re-exports. Food re-exports were estimated by 8%, globally (MacDonald et al., 2015). Using the FAO FBS data, food consumption of domestic origin turns into negative. It makes conduction of the LMDI still possible technically, since it compares the log-differences of variables; unless its operations are mathematically incorrect, as it was the case in the first two years of WE decomposition. One should be aware, though, that the lack of robust estimates on the level of re-exports, the amount of domestic supply is rather uncertain. Assuming a constant level of re-exports, our data report on a low and stable variation of MF, within the range of 0.1%–5%; negligible, but merely positive structural effects, and slightly increasing intensity. The intensity of imported products is rising permanently, and its level was higher by 22% in 2013 compared to the first year of the analysis (1990). Therefore, as consumption volume and structure do not influence the MF significantly, effects of domestic material efficiency gains are leveled off by the increasing intensity of imported goods. Our findings are close to Roux et al. (2021), who revealed the trade to enhance the MF growth in the EU15+ country group.

The rising share of processed food in imports is a global trend; however, it is coupled with worsening efficiency in the WE region exclusively. On the one hand, one can presume, that the intention to importing food is not driven by the demand for food of the society of WE countries, but the demand along the continental and global food supply chain managed by multinational companies resided in the WE region. For that end, a redundant extension of the food supply chain may vanish the gains of the comparative advantages with regard to natural resources–if constant re-export share is considered. On the other hand, assuming the emerging rate of re-exports, the increasing intensity is just a biased result of food consumed outside the region, leading us back to the original accounting issue. If this is the case, the negative effects of international trade are overestimated. Nevertheless, the food MF in WE has risen by 15%, anyway, by nearly constant consumption volume and structure, and overall intensity. Consequently, the decomposition results are dependent on the data for the extent, if domestically produced or the imported food intensity has risen faster. The accounting for re-exports is undoubtedly a key toward further research efforts.

Table 2 reports on a relatively stable structure of the MF regarding its material composition and sectoral origin. WE region is characterized by the highest level of import share in MF by far. According to the results, the EER region witnessed significant efficiency improvement after the political restructuring, as the fossil fuel MF has dropped by 20%, in line with slightly emerging food consumption. Nevertheless, the overall MF increased by 84%. A similar trend is observable in the WE region; however, in the former region, the fossil fuel's energy improvement was offset by another type of resource use; the latter region's domestic MF was reduced absolutely.

The table also presents that biomass, as the aggregated mass of primarily harvested phytomass and wild catches, dominates the MF, while construction minerals and fossil fuels are minor contributors to the production. The share of processed food is the highest in the WE region, which manifests in the high portion of industrial inputs, that is, fossil fuels and construction minerals. The biomass part of the MF is the highest in MA region by far; however, the processed food ratio exceeds the global average. The share of agricultural products in consumption (89%) exceeds those of other regions in the sample and the global average as well (81%). Besides, these commodities' intensity is significantly lower than the global average, as described above, which makes the share of primary products lower in MF.

Table 2
Physical and Sectoral Components of the Material Footprint at Global and Regional Scale

		Material components (%)				Sectoral structure (%)			
		Biomass	Fossil fuels	Construction minerals	Metallic ores	Agriculture	Fishing	Processed food & Beverages	Import (%)
World	1990	83.2	6.4	7.9	2.5	37.5	1.1	61.4	9.1
	2002	81.9	5.9	10.7	2.5	39.2	1.6	59.2	10.5
	2013	80.0	5.1	12.3	2.7	38.9	1.8	59.3	11.5
Central & South Asia	1990	94.9	1.5	3.2	0.4	46.7	0.2	53.1	4.4
	2002	92.7	1.7	5.0	0.6	47.0	0.2	52.9	7.1
	2013	91.7	1.8	5.6	0.9	47.6	0.2	52.2	9.3
Eastern Europe and Russia	1990	62.3	21.0	11.1	5.7	43.8	1.3	54.8	10.9
	2002	85.5	5.7	6.1	2.7	43.8	3.8	52.3	6.4
	2013	82.6	6.3	8.4	2.6	43.2	4.3	52.5	7.5
Middle Africa	1990	95.5	0.5	0.9	3.2	31.0	0.0	68.8	4.3
	2002	98.3	0.3	0.7	0.7	35.8	0.0	64.2	5.5
	2013	96.6	0.5	1.4	1.5	33.9	0.0	66.0	5.5
Western Europe	1990	76.2	11.6	10.0	2.1	20.8	0.2	79.1	20.5
	2002	76.6	8.1	12.5	2.8	20.3	0.2	79.6	25.8
	2013	75.4	8.1	13.6	2.9	21.1	0.2	78.8	34.0

3.3. Results of the Decomposition Analysis in a Sample of Seven Countries

In this section, the EXIOBASE v3.2 was utilized, which provides a significantly broader product resolution. Therefore, although it comes with current prices, it was utilized in country-level assessments to reveal the within-country trends of resource allocation.

Country profiles in Section 2.2 of the Supporting Information report the main characteristics of seven analyzed countries (profiles), with special regard to the share of imports, intensity and changes in consumption of distinct food products. Here, we displayed the Hungarian profile in Figure 4 as an example on the one hand, and also in order to complement the findings in Section 3.4. While in Figure 4 only those food categories above three percent of the total MF were displayed, all products are available in the Supporting Information.

The material intensity of several products varies in broad ranges, which accompanies all the countries' datasets. Mathematically, it is rooted in minimal amounts of imports or consumption of a domestic origin product. Limited product flows can occur either due to a large amount of re-exports (several sectors in DK) or negligible trade activity (e.g., dairy production in the 90s in HU). Unfortunately, a few initial data issues harm both the FAO and the EXIOBASE data tables, resulting in one year's excess product flows or MF. Nevertheless, all these biases concern an irrelevant amount of MF because of the low amount of flows or insignificant occurrence; therefore, the decomposition results are not systematically harmed.

Between 1995 and 2013, the food MF has been increased in BR, CN, and PT among analyzed countries. The contribution of the food imports (Trade) to the food MF in PT, DK, HU, and PL were negative in the majority of the periods covered. The trade was the largest factor acting against the MF growth in these countries, making MF able to decrease in time.

Although our comparison is not based on a representative sample of counties, BR is far less in need of food imports than the seven analyzed countries. Furthermore, the only one where the trade patterns (low level of food imports) result in additional food MF. However, remarkable growth in food MF of BR is driven by the rapid population growth, which has emerged from 160 million inhabitants in 1995 to 200 million in 2013. The Brazilian diet leans on animal products above the global average, and the consumption of these products kept increasing in the analyzed period. The ascending trend, however, was interrupted several

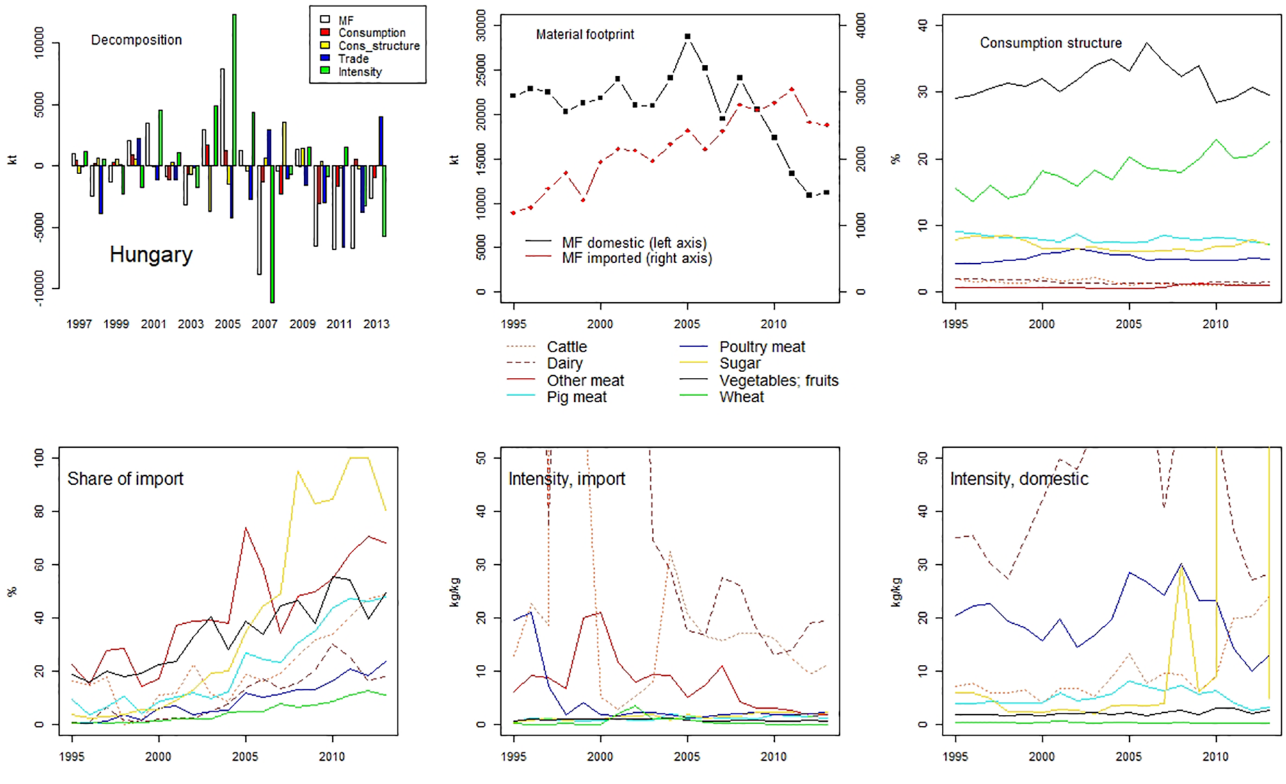

Figure 4. Country profile of Hungary.

times. According to the FAO database, the per capita intake of animal products' caloric value even dropped in 2001 and 2005. These counter-movements of the general trend are reflected in the structural factor of the decomposition.

On the contrary, consumption structure was the most significant factor of the emerging food MF in CN; it is evident in a country, where meat consumption has doubled in the analyzed period, to reach to Western level at the end. Significant counteracting factor in CN is the efficiency improvement, which delivers lower resource use at the level close to that of total consumption volume, but with a negative sign. In this point of view, TR shares this basic feature of development with CN; however, TR has passed the nutritional transition already; thus, its total consumption is stable, and the efficiency gains support the emerging exports of the country. In the developed countries, the intensity has descended after 2008, which may be a reaction to the long depression and stagnation after the crisis and to the competitive environment through the intensifying international trade.

In case of HU, eight food product groups exceed 3% of the total food-related MF. With regard to imports of these products, it has started to intensify at the beginning of the 21st century. The next remarkable ascend in the food imports is observable in 2004–2007, following the EU accession of the country in 2004. Significantly increasing imported amount of sugar, pig, cattle, and poultry meat is reported by Figure 4. It is worth to declare, that those three years meant a trend shift in Hungarian international trade, since both food commodities, and general net exports have turned into positive. Consequently, the access to the EU's joint markets resulted in an intensification of the international trade in general, in which HU participates preferably with bulk commodities (cereals, other crops) as a major exporter–being self-sufficient in the same time.

The intensity of imported food seems to decrease in line with emerging imports, while the intensity of domestic nutrition is more volatile. The domestic intensity of sugar production is not robust at all; hence there is no domestic production practically. The intensity of poultry, pig and other meat is a magnitude higher in domestic production, then that of imported products. The case of the dairy products is noteworthy; the intensity of imports dropped by 75% each year between 2002 and 2005, and it remained significantly lower for a long time. Efficiency improvements have started in domestic production after the year 2010, and a negative trend in the share of imports launched in parallel to this improvement.

Food products exceeding 3% of total MF were displayed for improving the visibility of the main effects. All the results are provided in the Supporting Information. Plots in the top left and top middle position are presented with separated legend, while the legend of the remainder is placed in the center of the figure.

The consumption structure, population, and trade patterns of PT and DK are relatively stable for a long time (Section S2.2, Supporting Information). The changes of MF in two years (chained decomposition) do not exceed 7% of the MF and generally are within a range of 2%–5%. A slight increment in import share is observable after 2008 in PT, and also the efficiency of the production of imported goods improved this time, especially in the case of other meat, cattle and dairy products. This trend is also evident in the long-term. A similar process is reported in DK, but earlier, at the beginning of the analyzed period.

The case of PL is instructive, as the Polish agriculture and food industry became one of the most competitive among EU members after the accession in 2004. Indeed, PL successfully improves the efficiency of domestic production of its competitive food products that is, milk, dairy, pig, and poultry meat. In the same time, the import share of these products emerges moderately, while the intensity of this import also shows a descending trend. These animal products with a high MF, thus, followed a descending trend of MF, regardless of the origin, and also exports of PL constitute a significant part of consumption in other countries.

TR and CN consider the efficiency of domestic production as a strategic priority. Our data imply that they are doubtlessly successful; both countries' major negative contributor to variation in MF is the intensity by far. Domestic food MF of TR in 2013 was approximately one-fourth of that in 1995. The intensity of consumption from domestic sources in case of dairy products, eggs and fats, poultry and cattle meat dropped rapidly. As a consequence, the share of imports in these commodities started to decrease last years as well. On the contrary, China's consumption volume and structure has gone through an enormous change. Therefore, significant efficiency gains of food production could not counteract volume and structural effects.

Since animal products (i.e., meat, milk, dairy products, eggs, and fats) are characterized by MF higher with at least one order of magnitude, they tend to imply significantly more differences in their intensity by the origin. Therefore, the lower intensity is a strong incentive to substitute domestic animal products through import, while resource use of plant products is found in a narrow range. Plant products are probably imported in case of lack in self-sufficiency exclusively, as in PT in our sample. Furthermore, imports of food products of lower intensity will result in a rapid fall in MF in case of animal products, in contrast to the plant products. It is applicable for any source of efficiency improvement, obviously; however, efficiency improvement of the domestic production is a long-term process, requiring knowledge transfer and investments.

Considering our country sample, the imported product's MF is consistently lower than the commodity's domestic counterpart, which justifies material savings. The occurrence of the savings is ambiguous, though, if one focuses on the net exporter countries. Their efficiency does not exceed those of importer countries generally. The lower intensity of exporters applies in the case of dairy products (DK and PL), other animal products (DK, PT, TR, and PL), vegetable oils (HU and BR), and vegetables (BR, CN, and TR). Some excellent examples illustrate the ongoing trend shift in trade direction in line with efficiency improvement due to industrialization, as it will be discussed further in Section 3.4. In TR, for instance, the domestic intensity of other animal products dropped dramatically, from 61 t/t to 0.2 t/t. At the same time, imports have halved, and exports raised 18-fold, to become 14% of the inland production. On the contrary, some products are characterized partially by a lower efficiency of the exporters, for example, the domestic intensity of pig meat production is significantly higher in HU, as net exporter (ranging from 2.7 to 8.2 t/t) than in PT (1.5–2.2 t/t), as a net importer. The same contradiction applies to poultry, other meats, cereals, beverages, and cattle meat.

The plausible explanation of this very phenomenon is threefold; it constitutes a conceptual and a study-specific, technical one. First, the comparative advantages may lean on other production factors. The cattle production in BR, being the largest and the less effective cattle meat producer among analyzed countries, discussed further in Section 3.5, clearly presents. According to the theory of comparative advantages, exporter parties do not presume to deliver superb productivity but lower alternative costs. In other words, the best allocation of resources within an economy is decisive; thus, a country's supply chain might be even the worst concerning all food products, the opportunity cost of production turns out to be the lowest among trading partners in at least one of the commodities. Second, according to the new theory of trade, a limited set of companies can maintain high productivity and sell products abroad at a remarkable profit rate (Bernard et al., 2007; Melitz, 2003). In this way, several actors may drive the international flows of commodities, while others "pulling down" the average productivity. Third, our sample includes seven individual countries. It is plausible that net exporter countries of several products are found outside this sample. In fish production, for instance, none of these countries are net exporters. The closest to this position is CN, and its domestic intensity tends to decrease in those periods when imports drop and exports intensify. Nevertheless, at the global level, the intensity of food products of domestic origin has slightly worsened while that of imported has improved. The intensity of primary sectors (agriculture and fishery) stagnates, whereas the intensity of global domestic production ascended by 25%, and the intensity of the imported product dropped by 31%.

3.4. International Trade and Capital Stock

During the transition of the socio-economic system in last decades, material stock accumulation became the major driver of natural resource use. Material stock provides essential services for society, and thus in line with emerging affluence of a society, material accumulation intensifies. It is a socio-economic process with unprecedented growth; ratio of stock building materials has raised globally from 20% to 58% of the DE between 1900 and 2010 (Krausmann et al., 2017). Stock accumulation, however, challenges the ecosystem with an increased amount of mineral waste, energy consumption and requirements for construction materials (Haberl et al., 2017; Weisz et al., 2015). Therefore, any policy toward sustainable management of natural resources should address material stock as well.

Capital stock is the subset of material stock inevitable in the production of goods and providing services. Their assets are estimated to reach 40%–55% of total material stock, and their amount rises rapidly (Cao et al., 2017; Ortlepp et al., 2015). Despite the apparent significance of the capital stock, the estimation of this type of assets is somewhat unsolved yet. It would be challenging, thus, to assess the coevolution of capital's material appropriation along with the intensification of the international trade. In this section, we discuss the nexus of capital stock and the trade. We interpret the stock-building material content of our country-level results first. Afterward, existing data in HU, as the only country with sectoral-level data by this time are introduced; and a trade-off between the efficiency gains and the international trade is presented as well.

The share of mineral inputs into the food supply chain raised significantly between 1995 and 2013 (Table S2). This variable is assumed to correlate to construction materials strongly. It provides thus a good approximation of material inflows supporting capital formation. The only exception for the increasing mineral input in our sample is BR. Its efficiency, however, was far less improved, compared to other countries, as it was discussed above in Section 3.3. CN and TR, as it was introduced formerly, follow a strategy of domestic efficiency improvement. Here, MF of imported food is extremely low in total food MF; and increment in overall mineral MF is driven by domestic advances. A sort of "outsourcing" of investments into the food supply chain features DK, HU, and PL. It is reasonable to avoid those investments for a society, when it is better off to participate in international trade instead.

Intensification through industrialization is observable concerning animal products. While most plant products' MF consists mainly of biomass (approximately 95%), animal products' MF biomass share ranges from 60% to 80%. The only exception is the bovine meat production (above 90% biomass content of the MF), as it is technology is extensive typically. Whereas the emerging share of construction materials and metallic ores in the MF of plant products is infrequent (e.g., vegetables in PL), the animal products' MF generally shifts toward ascending material stock requirements accumulation.

Table 3 illustrates the process of utilizing the domestic MF data of dairy products in PT. In the period analyzed, the production has nearly doubled, imports and exports have intensified and balanced. Total MF has increased by 32%, while domestic MF emerged by 22%, resulting from the increasing non-metallic mineral usage exclusively. Since this material category consists mainly of construction materials, this effect is attributable to construction activity along the dairy supply chain. The trade-off between the flow-type efficiency

Table 3
Components and Structure of the Domestic Material Footprint (MF) of Dairy Products, Portugal

	Aggregated	Biomass		Fossil fuels		Minerals		Metallic ores	
	kt	kt	%	kt	%	kt	%	kt	%
1995	826	572	69.2	72	8.7	161	19.5	21	2.5
1996	931	618	66.4	82	8.8	208	22.3	23	2.5
1997	943	607	64.4	77	8.2	238	25.2	21	2.2
1998	1,026	657	64.0	105	10.2	238	23.2	26	2.5
1999	1,118	692	61.9	108	9.7	292	26.1	26	2.3
2000	1,060	594	56.0	65	6.1	381	35.9	20	1.9
2001	1,057	585	55.3	69	6.5	382	36.1	21	2.0
2002	1,076	556	51.7	74	6.9	423	39.3	23	2.1
2003	1,074	534	49.7	86	8.0	429	39.9	25	2.3
2004	1,137	534	47.0	97	8.5	478	42.0	28	2.5
2005	1,045	471	45.1	83	7.9	463	44.3	28	2.7
2006	1,131	454	40.1	91	8.0	552	48.8	34	3.0
2007	1,229	476	38.7	111	9.0	615	50.0	27	2.2
2008	1,390	566	40.7	114	8.2	681	49.0	29	2.1
2009	1,214	504	41.5	105	8.6	585	48.2	20	1.6
2010	1,157	493	42.6	67	5.8	575	49.7	22	1.9
2011	1,197	536	44.8	74	6.2	566	47.3	21	1.8
2012	1,050	475	45.2	56	5.3	501	47.7	18	1.7
2013	1,007	510	50.6	53	5.3	425	42.2	19	1.9
2013/1995	1.22	0.89		0.74		2.64		0.90	

and the material requirement was recently discovered (Chester et al., 2019; Luderer et al., 2019; Whiting et al., 2020). It applies here as the efficiency gains in energy consumption and feed input, for instance, calls for improvements in the production technology by the cost of accelerating investment activity. This phenomenon is observable throughout the whole country-level sample; however, since the biomass performs some efficiency gains in all cases, the fossil fuels MF contributes to growing MF, for instance, in polish pig and poultry production. Furthermore, the trend of increasing material accumulation may slow down in line with the supply chain's development. For example, dairy and pig meat production in DK changes its MF composition significantly slower.

For HU, estimation on NAS and the total amount of capital stock is available at sectoral level (Dombi, 2019), as an indicator of the material stock accumulation. If NAS does not drop together with food MF of HU, it might reflect, that the intensification of international trade is supported by the food supply chain's increasing stock accumulation. Nevertheless, the results imply that MF was less affected by the stock accumulation in case of agriculture; compared to the food industry, which calls for a lower amount of stock accumulating material in case of lower food MF (Table S3 and Figure 5.). These results resonate the trend of stock accumulation due to increasing production of agricultural raw material for intensive export; which, however, manifests in other countries' MF (for cereals, mainly). Capital stock accumulation processes in the domestic food industry are, however, moderate in line with rising demand for imported processed goods–animal products, respectively. In other words, if import allows for consuming the same products by lower MF (mainly biomass), decreasing MF accompanies the fall in investments into the domestic food industry, since those commodities are purchased as finished goods. Investments into agriculture are less sensitive to food MF; hence the products of the sector have its well-established export markets.

Trends in capital stock accumulation underpin the theory of MF's strong reflection on the structure of international trade. The capital stock of the service sector has been grown more intensely than agricultural

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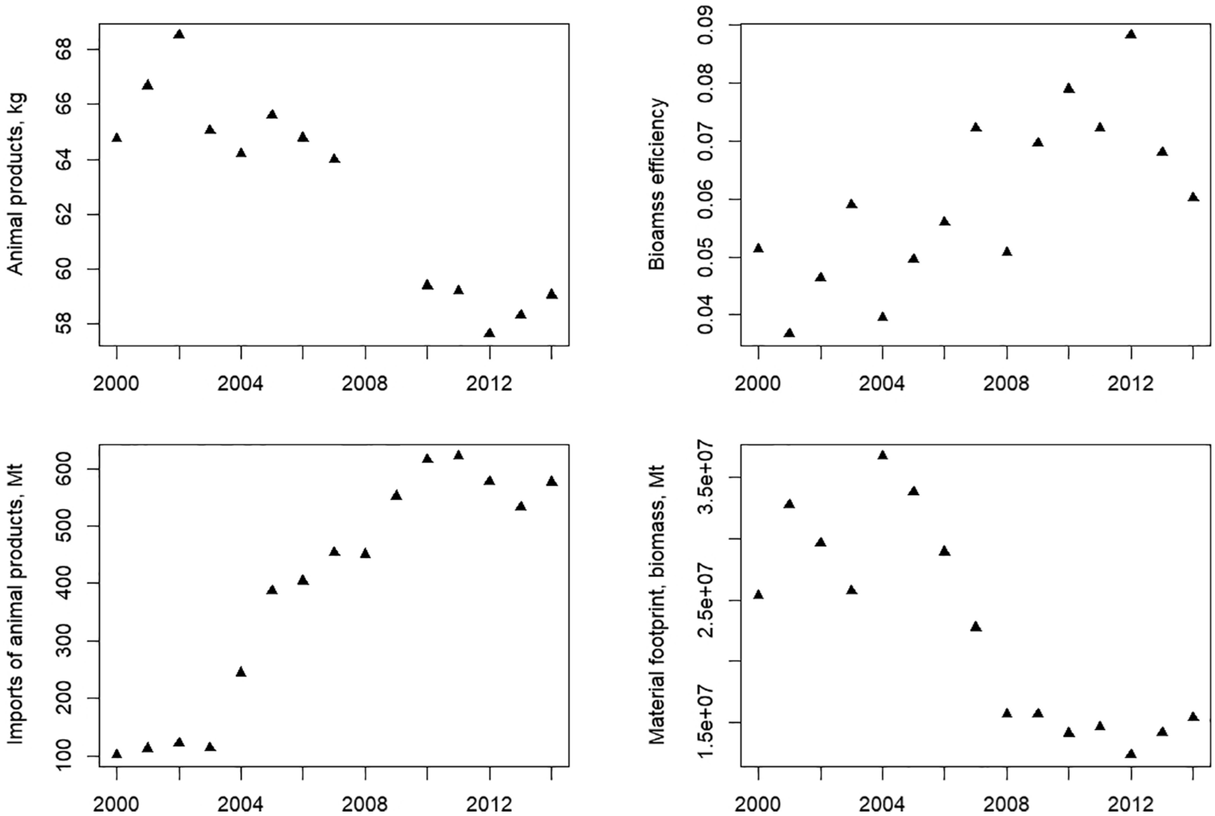

Figure 5. Interdependence of capital stock and material footprint in Hungary.

production and food industry (Figure 6). If one compares stock accumulation along the food supply chain, it is significantly faster in the agricultural sector (~50%) than in the food industry (~6%). On the one hand, the food industry is a traditional sector of the Hungarian economy, so it is likely, that a large amount of capital stock has been established for a long time already. On the other hand, food commodities requiring a high level of processing were imported intensely in the last decade; thus investments have slowed down. Food industry's contribution to GDP is decreasing as well, its share in income generation was 2.8% in the year of EU accession (2004), while 2.2% in 2014. Its gross value added increased only with 2% in that period, in contrast to 16% increment in agriculture, 20%–30% in some service sectors and 24% generally.

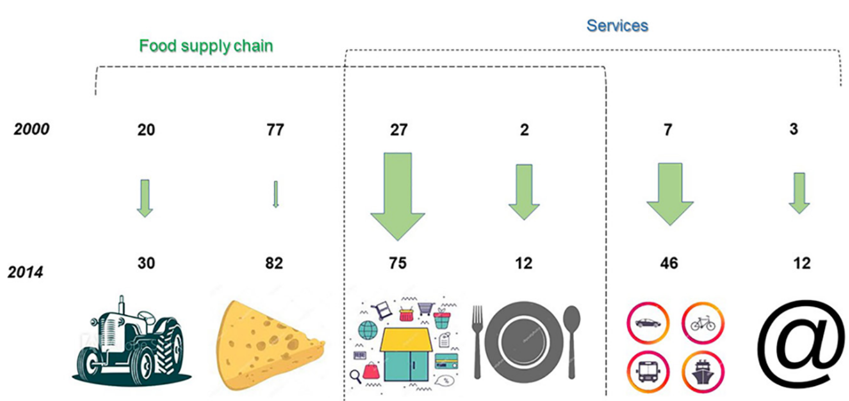

Figure 6. Evolution of capital stock accumulated in several sectors between 2000 and 2014, Hungary, Mt. Sectors from left: agriculture and fishery, food industry, trade and storage, restaurants and hotels, transportation, and communication services. Results of the trade sector are not statistically robust.

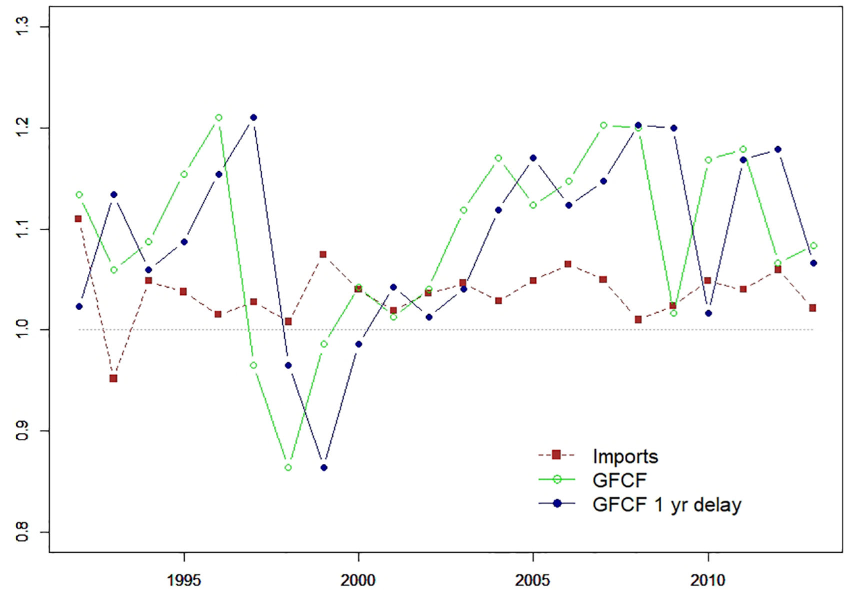

Figure 7. Annual changes in imports and the gross fixed capital formation at global scale.

As the Hungarian case suggests, an economy's infrastructure adjusts toward international trade patterns. It shed light on the remarkable counter-movement of MF changes induced by the trade and the intensity, observable in the decomposition results (Figure 2, and Section S2.2). Figure 7 implies that the international trade and investments indicated by the GFCF in the national accounts are substitutes to some extent. The opposing direction of trends is well-expressed if we allow a year delay in the effect of the investments to present the efficiency effects extension over the agricultural season (blue line in the figure). As efficiency improvements are partially delivered by these investments, along with managerial, instrumental, and other origins of efficiency gains, one may assume that investments are coupled with the emerging competitiveness of domestic production on the inland and global market. Former empirical shreds of evidence underpin our findings that investments tend to intensify exports and mitigate import dependency (Jackson & Jabbie, 2020; Marchant et al., 2002).

Nevertheless, massive investments into the food supply chain did not prevent the rapid ascend in the material intensity in the period 2003–2009. At this time, all the components of material inputs have intensified. The biomass and fossil fuels MF has grown 2%–4% and 2%–5% annually, respectively. The growth rate of mineral and metal usage, though, has even reached 9%. Investments, therefore, did not translate into efficiency gains. Meanwhile, the three sectors (agriculture, fishery, and food industry) have stagnated in their share globally; therefore, the structural effects of consumption remain moderate. Consequently, the efficiency gains have been offset probably by the industrialization process introduced by the country-level sample formerly in this section.

3.5. Other Environmental and Social Impacts–An Outlook

The potential gains of international trade were emphasized in this study so far. As globalization is one of the more complex global processes, however, it should not be oversimplified. Although motives described by the theory of comparative advantages forms the global trade, as we presented; at least two considerations with regard to adverse socio-ecological effects should be issued. First, one could be addressed as the justice dimension of the international trade, referred to as the legal, income, labor, cultural, and ecological consideration. Second, our measurement of MF may fail significant social and environmental impacts, despite the mature methodological applications. In the following section, a brief discussion on these effects is provided.

The case of Brazilian meat export provides an example of theoretical bias. BR exports a vast amount of meat (15% of bovine and 25% of poultry meat globally), although the intensity of the domestic production is higher than in other analyzed countries in many cases. Moreover, intensity contributed to rising MF in majority of years in analyzed period (see Section S2.2 of the Supporting Information). Our findings resonate the results of Tian et al. (2020); that is, BR witnessed negative decoupling of economic output and water, land, material, carbon, as well as sulfur footprints between 2000 and 2014. It is presumed, that the competitive price of that commodities is not based on natural resource efficiency, but on low wages, poor animal welfare standards, and available soybean stocks, leading to rapid deforestation in South America.

Along with the natural resource efficiency, other resources are objects of efficiency improvement (lower alternative costs) during the trade. Obviously, the same endowment of capital and labor will contribute to the increasing amount of food production, if the assumptions of the model of the comparative advantages hold. In fact, this effect of international trade is politically not attractive at all in those regions with a significant share of the population dependent upon the food supply chain, as in developing countries. There is a strong incentive for protectionism for that end even in Europe–almost half of the EU budget is dedicated to those rural regions and agricultural stakeholders, either in a direct or a hidden way. Nevertheless, employment seems to be not harmed by international trade (see results and discussion in the Supporting Information).

Developed countries are foreseen to outsource their environmental impacts for an extreme level. In a study on Swiss food consumption, Scherer and Pfister (2016) found that although two-thirds of the food was produced domestically, 97% of water usage, 92% of the phosphorous emission, and at least 96% of biodiversity loss was dedicated to imported food. Biodiversity related ecological issues are at the core of the international and any development discussion. Marques et al. (2019) modeled the role of trade in global biodiversity loss and carbon sequestration between 2000 and 2011. They found that the role of trade in 2011 was significant indeed, 25% and 21%, respectively; however, it represented 3% and 1% increase in 11 years. In the same period, the amount of global food exports rose by 50%. It would be worth to model as well, how these measures would perform under a "no trade" scenario.

Malik et al. (2018) discussed the ability for extending MRIOTs with social indicators, like the Global Hunger Index (GHI) to assess the role of trade in front of SDGs. Schaffartzik et al. (2019) found increasing material inequality due to international trade. The socio-ecological effects of globalization are still endless, though. Steen-Olsen et al. (2012) point out that the displacement of environmental pressure through trade maybe even beneficial, and the potential negative impacts depend on local conditions. Wiedmann and Lenzen (2018) advice to extend the models for a better understanding of the local context of scarcity, risk, and vulnerability. Several efforts toward more detailed, accurate and sub-regionally relevant footprint models were launched recently (Bruckner, Hayha, et al., 2019; Bruckner, Wood, et al., 2019).

Food waste is an issue with outstanding importance as well. There is a possibility to construct waste input-output tables (WIO) at regional or country level, to also cover the flows of lost natural resources due to processing, packaging and wasting along the whole supply chain (Corrado et al., 2019; Nakamura & Kondo, 2018; Tisserant et al., 2017). With regard to the high data demand of a WIO, and the data scarcity on the field of waste management, global assessment of that kind is rather unrealistic.

Countries with increasing food import reinforce their efficiency improvement with the lower resource intensity of imported goods. Nevertheless, harmful social and environmental impacts indeed accompany globalization. Consequently, trade liberalization, combined with a regulation focusing on the negative impacts, could be an appropriate policy direction (Kehoe et al., 2020). Furthermore, the local social context should be considered and respected as well. Novel databases with higher commodity and regional resolution as recently introduced FABIO promises a better understanding of social and environmental impacts of the trade (Bruckner, Wood, et al., 2019). As presented above, many ecological and social effects of globalization should be considered in the future. Biodiversity loss, deforestation, mining activity, landscape effects, eco-toxicity as environmental pressures; while social conflicts, as child labor, social inequality, corruption are not reflected enough yet.

4. Conclusions

Our results indicate that the optimization of the food supply through trade may contribute to the reductions of resource use. The actual food consumption would lead to significantly higher MF by limited global food availability for trade. Decomposition on the global scale reveals that population growth is the primary factor to increase natural resource use, while trade is the one which counteracts it. Nevertheless, our concept of the consumption structure may underestimate effects of the dietary change. These results show a fundamentally different picture than decomposition focusing on overall resource use of aggregated consumption by Plank et al. (2018); involving all the types of goods, from fuels to construction materials. It highlights the reasonability of disaggregated analyses toward the well-targeted policy.

Regional and country-level assessments report that intensification of the international trade has significant effect on the MF of food consumption even in short-run, for example, years after EU accession process or after the economic crisis in 2008–2009. The incentives for trading due to internationally comparable intensity measures were also proved, however, the Brazilian case highlights that multiple production factors should be considered. The analysis also revealed that regions characterized by rapid population growth accompany low structural effect of MF variations (CSA and MA regions, BR).

Examination of the bonds between the international trade and the material stock of the food supply chain suggests that the amount and structure of traded commodities affects the accumulation process significantly. Country-level analyses and the Hungarian case study reported on intense reaction of the stock accumulation on trading trends in material terms. International trade, thus, might have multiplicative effects on resource use through the stock accumulation, which underpins its impressing role toward the decoupling of natural resource use from economic growth. Furthermore, some evidence has been found for imports and domestic efficiency improvements to be partially substituted. However, on a global scale, material stock accumulation vanished the effects of the emerging material efficiency in the 21st century.

The results of our global and regional assessment are valid if the actual food consumption is considered. However, the question remains, whether the trade increases the natural resource use due to making the excess amount of food available for the society via the global food supply chains. Considering our results at global and regional scale, the role of international trade in the use of natural resources can be viewed rather as two sides of the same coin. It was argued that the influence of animal products' trade flows on the MF is remarkable; consequently, emerging MF due to structural changes in food consumption accompany the reduced MF by trade, as optimization of animal products' resource allocation affects the footprint intensely.

Data Availability Statement

All the food consumption and supply data can be available from the FAOSTAT Food Balance Sheets Database (at http://www.fao.org/faostat/en/#data/FBSH), elements of the EXIOBASE MRIOTs are available upon registration (at https://www.exiobase.eu/index.php/data-download/exiobase3mon), while EORA26 MRIOTs are available upon registration (at https://worldmrio.com/eora26/).

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