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Subnational greenhouse gas and land-based biodiversity footprints in the European Union

Harry C. Wilting¹ | Aafke M. Schipper^{1,2} | Olga Ivanova¹ | Diana Ivanova^{3,4} | Mark A. J. Huijbregts²

¹ PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands

² Department of Environmental Science, Institute for Water and Wetland Research, Radboud University, Nijmegen, The Netherlands

³ School of Earth and Environment, University of Leeds, Leeds, UK

⁴ Norwegian University of Science and Technology (NTNU), Trondheim, Norway

Correspondence

Harry C. Wilting, PBL Netherlands Environmental Assessment Agency, P.O. Box 30314, 2500 GH The Hague, The Netherlands.
Email: Harry.Wilting@pbl.nl

Editor Managing Review: Richard Wood

Abstract

Insights into subnational environmental impacts and the underlying drivers are scarce, especially from a consumption-based perspective. Here, we quantified greenhouse gas (GHG) emissions and land-based biodiversity losses associated with final consumption in 162 regions in the European Union in 2010. For this purpose, we developed an environmentally extended multi-regional input-output (MRIO) model with subnational European information on demand, production, and trade structures subdivided into 18 major economic sectors, while accounting for trade outside Europe. We employed subnational data on land use and national data on GHG emissions. Our results revealed within-country differences in per capita GHG and land-based biodiversity footprints up to factors of 3.0 and 3.5, respectively, indicating that national footprints may mask considerable subnational variability. The per capita GHG footprint increased with per capita income and income equality, whereas we did not find such responses for the per capita land-based biodiversity footprint, reflecting that extra income is primarily spent on energy-intensive activities. Yet, we found a shift from the domestic to the foreign part of the biodiversity footprints with rising population density and income. Because our analysis showed that most regions are already net importers of GHG emissions and biodiversity losses, we conclude that it is increasingly important to address the role of trade in national and regional policies on mitigating GHG emissions and averting further biodiversity losses, both within and outside the region itself. To further increase the policy relevance of subnational footprint analyses, we also recommend the compilation of more detailed subnational MRIO databases including harmonized environmental data.

KEYWORDS

biodiversity loss, footprint analysis, greenhouse gas emissions, industrial ecology, multi-regional input-output analysis, subnational assessment

1 | INTRODUCTION

There is growing awareness in European Union (EU) policies that consumption in the EU has impacts in regions all over the world and that environmental responsibility should not be limited to the EU territorial borders (EEA, 2019). The European Commission (EC) states in its Biodiversity Strategy to 2020 that "... the EU derives significant benefits from global biodiversity and is at the same time responsible for some of the loss and

degradation that occurs beyond its borders, notably due to its unsustainable consumption patterns" (EC, 2011a). The EU's long-term strategic vision for a climate neutral economy mentions trade policy as an instrument that could "*potentially support the reduction of the carbon footprint of all products consumed in the EU, including imported ones*" (EC, 2018). The growing interest in impacts via imports has led to the development of consumption-based indicators that connect consumption activities in a region with production elsewhere by considering complete supply chains including all environmental pressures or impacts domestically and abroad (Hoekstra & Wiedmann, 2014). In this study, we will use the term footprint for such regional consumption-based pressure and impact indicators, although we are aware that the term footprint is also used in other contexts at different scales (Fang et al., 2016).

Studies on the environmental footprints of nations are rather common now and have been performed for various environmental pressures and impacts, such as greenhouse gas (GHG) emissions, use of natural resources and biodiversity loss (for an overview see Wiedmann and Lenzen (2018)). Differences in footprint indicators between countries are related to geographical, demographic, or socioeconomic factors. By identifying these factors, footprint studies deliver additional information for policies directed at reducing environmental pressures and impacts via changes in consumption or trade patterns (Barrett et al., 2013; Ivanova et al., 2018). Footprint studies specifically focusing on the EU were performed for GHG emissions and the use of land, fresh water, and raw materials (Beylot et al., 2019; de Boer, Rodrigues, & Tukker, 2019; Serrano, Guan, Duarte, & Paavola, 2016; Steen-Olsen, Weinzettel, Cranston, Ercin, & Hertwich, 2012; Tukker et al., 2016). Koslowski, Moran, Tisserant, Verones, and Wood (2020) quantified the biodiversity-related impacts associated with European household consumption.

The EC underlines the importance of regional and local policies in its climate and biodiversity strategies (EC, 2011b). Up to now, the focus of subnational policies and mitigation measures has been on domestic emissions and biodiversity losses, without taking into account impacts outside the region. Connecting production and consumption regions within and outside Europe could help identify possible unwanted side effects, including outsourcing of emissions and biodiversity losses, of such subnational territorial policies. Furthermore, insights in subnational footprints and the underlying driving forces could help to refine existing national consumption-oriented policies and strategies, and to ensure policy coherence at national and subnational levels.

As far as we know subnational footprints in the EU are unavailable for biodiversity loss and are incomplete for GHG emissions. Ivanova et al. (2017) quantified GHG footprints of household consumption in 177 regions in the European Union (EU) and found significant differences in footprints between regions in the same country, mainly driven by differences in income. Mieke, Scheumann, Jones, Kammen, and Finkbeiner (2016) analyzed differences in GHG footprints of household consumption in the 16 federal states of Germany and reported income and household size as the main drivers. These two studies, however, specifically focused on household consumption and not on other final demand categories, including government consumption and investments, and therefore these footprints do not add to global totals of emissions and impacts. Furthermore, they distinguished subnational differences in consumption only, while not considering differences in subnational production and trade structures, which may be quite different from the average national structures (Los, Chen, & Thissen, 2017).

Here, we quantified GHG footprints and land-based biodiversity footprints in 162 regions covering the EU-27, taking into account subnational demand, production, and trade structures. The United Kingdom that left the EU in 2020 was considered as an EU country in our analysis; Croatia, which joined the EU in 2013, was not included due to data limitations (see Section 2.2). We performed the analysis for 2010, which was the most recent year for which subnational input-output data were available. We investigated the variation in footprints at the subnational level, the contribution of final demand categories to total footprints and the role of trade. Furthermore, we analyzed the relationship of these subnational footprints with three socioeconomic explanatory variables that may influence environmental footprints: per capita gross domestic product, population density, and the Gini index. The latter is included to test whether a region's footprint may change depending on income equality.

2 | METHODS AND DATA SELECTION

2.1 | Model structure

We employed an environmentally extended multi-regional input-output (EEMRIO) model for calculating environmental footprints of subnational regions in the EU. EEMRIO models give useful insights into the relationships between consumption in one region and local production and related pressures in other regions connected by interregional trade flows (Wiedmann & Lenzen, 2018). The equation for the GHG footprint, G^j , of region j was:

$$G^j = g E(I - A)^{-1} y^j + g e^j \quad (1)$$

with g the vector of global warming potentials per GHG; E the matrix of direct GHG emission intensities per sector and region per GHG; $(I - A)^{-1}$ the Leontief-inverse matrix including the identity matrix I and the technological matrix A representing direct inputs per unit of production in all sectors and regions; y^j the vector of final demand in region j and e^j the vector of direct GHG emissions by final consumers in region j .

The equation for the land-based biodiversity footprint, B^j , of region j was:

$$B^j = i(M \circ L)(I - A)^{-1}y^j + m^j \bar{l}^j \quad (2)$$

with i a vector of ones; M the matrix of biodiversity loss factors per sector and region per land-use type; L the matrix of direct land-use intensities per sector and region per land-use type; $(I - A)^{-1}$ and y^j as in Equation (1); m^j the vector of biodiversity loss factors per land-use type in region j ; and $\bar{l}^j$ the vector of direct land use per land-use type by final consumers in region j . Operator $\circ$ is the element-wise multiplication of two matrices. Section S1.1 in Supporting Information comprises a more detailed explanation of Equations (1) and (2).

2.2 | Data selection

2.2.1 | Input-output data

For the footprint calculations we used an MRIO table from EUREGIO, a global database with regional detail for Europe for 2000–2010 (Thissen, Lankhuizen, van Oort, Los, & Diodato, 2018). We used the table with data for the year 2010, since this was the most recent year available in EUREGIO. The EUREGIO database was compiled by downscaling the World Input–Output Database (WIOD), Release 2013 (Timmer, Dietzenbacher, Los, Stehrer, & de Vries, 2015), to 266 regions and 14 sectors per region (Tables S1.1–S1.3 in Supporting Information S1). The 266 regions included 252 subnational regions and individual countries in the EU, 13 large economies outside the EU and one region covering the rest of the world. The classification of the EU regions followed NUTS2 based on NUTS2006 (Eurostat, 2007). Croatia was not included as an individual country in EUREGIO, but as part of the rest-of-the-world region.

We adjusted the MRIO table obtained from the EUREGIO database in two respects:

- (i) we disaggregated the agricultural sector, which is rather heterogeneous with respect to GHG emissions and land use, into five more homogeneous subsectors, viz. crops, livestock with land, livestock without land, forestry, and fisheries, thus arriving at 18 sectors in total (Table S1.3 in Supporting Information S1). The disaggregation was based on Eurostat data on economic accounts for agriculture by NUTS2 regions (Eurostat, 2017a) in combination with shares from EXIOBASE version 2 data at the national level (Wood et al., 2014);
- (ii) we improved upon the regional final demand structures in the MRIO table, which were based on national final demand structures, by applying detailed household consumption data per region as compiled by Ivanova et al. (2017). These consumption data were available for 179 regions. The national totals of household consumption in the resulting adjusted table were kept consistent with the national tables originating from WIOD by applying RAS balancing procedures (Miller & Blair, 2009). We did not adjust the structures of the other final demand categories, viz. government consumption and investments, by lack of appropriate subnational data.

We included all 266 regions distinguished in the input–output table in our MRIO calculations, but aggregated the results to the 162 EU regions for which both input–output data and detailed consumption data were available (Text Section S1.2 and Table S1.4 in Supporting Information S1).

2.2.2 | Environmental data

We distinguished two main environmental pressures in our analysis: GHG emissions (CO_2 , CH_4 , and N_2O) for calculating GHG footprints, and land use (habitat loss, habitat fragmentation, and disturbance by infrastructure), as primary driver of biodiversity loss (Maxwell, Fuller, Brooks, & Watson, 2016; Pereira, Navarro, & Martins, 2012), for calculating land-based biodiversity footprints. Including environmental pressures, such as land use, in biodiversity footprints provides a more explicit relationship between human drivers and impacts on biodiversity (Hertwich, 2012). We used the Mean Species Abundance (MSA) metric as indicator of biodiversity since it directly links biodiversity losses to different land-use types. The MSA indicator expresses the mean abundance of original species in a disturbed situation relative to their abundance in undisturbed ecosystems (Alkemade et al., 2009; Schipper et al., 2020).

Because the EUREGIO database contains no environmental data, we collected them from different data sources using subnational databases as far as possible. Without sufficient and appropriate subnational sectoral GHG intensities, we used national direct GHG intensities for all regions in a country. We retrieved national data on GHG emissions for 2010 from EXIOBASE 3 (Stadler et al., 2018), which we aggregated to the 18 sectors and combined with national production data. We retrieved direct GHG emissions by consumers by combining regional shares of direct household emissions obtained from Ivanova et al. (2017) with national emissions published by EXIOBASE 3. We converted all GHG emissions into CO_2 -equivalents by using global warming potentials taken from Myhre et al. (2013).

We obtained sectoral direct land-use intensities per NUTS2 region for cropland, pasture land, forest areas, and artificial (built-up and paved) areas based on regional data on land cover and land use from the Land Use/Cover Area frame Survey (LUCAS) (Eurostat, 2017b). For the non-EU countries, the main sources for land-use data were FAOSTAT for cropland (FAO, 2017) and the GLOBIO 3 terrestrial biodiversity model for pasture land, forest areas, and built-up areas (Alkemade et al., 2009; Schipper, Bakkenes, Meijer, Alkemade, & Huijbregts, 2016). We retrieved the road lengths per country, needed to calculate the impacts of roads on biodiversity due to fragmentation and disturbance, from the GRIP database (Meijer, Huijbregts, Schotten, & Schipper, 2018). We started from national figures for this calculation, since regional transportation is in general not limited to the territorial boundaries of the region. The GRIP data set distinguishes five road types: highways (type 1), primary roads (type 2), secondary roads (type 3), tertiary roads (type 4), and urban/residential roads (type 5). The GLOBIO 3 model uses road length types 1–5 for calculating biodiversity losses by disturbance and road length types 1–3 for calculating losses due to fragmentation (see Section S1.4 in Supporting Information). We distributed the total road lengths per country among sectors and consumers using national fuel use data for transport of sectors and consumers obtained from Timmer et al. (2015). We allocated areas of buildings and paved surfaces, such as parking places and cemeteries, directly to final demand.

In order to quantify impacts from land use on biodiversity we linked MSA-loss factors for each land-use type derived from the GLOBIO 3 model (Alkemade et al., 2009; Schipper et al., 2016). These MSA-loss factors were based on country-specific GLOBIO 3 results for land use and related impacts on biodiversity, covering species from three major taxonomic groups (vertebrates, invertebrates, and plants). We distinguished MSA-loss factors for use of cropland, pasture land, forest areas, and built-up areas for disturbance by infrastructure and for fragmentation by infrastructure and cropland (Table S2.1 in Supporting Information S2). Especially the last three land-use types showed relatively large variation in the national MSA-loss factors. The derived MSA factors depicting the biodiversity losses from infrastructure were relatively large for countries with ample natural area without other drivers of biodiversity loss, such as Finland and Sweden. For further details on the environmental data and biodiversity-loss factors we refer to Sections S1.3 and S1.4 in Supporting Information. Section S1.5, Supporting Information describes the modeling software that we used.

2.3 | Relationships between footprints and explanatory variables

We conducted a multiple linear regression analysis for the 162 EU regions selected above to explore the relationships of the calculated per capita GHG and land-based biodiversity footprints with three socioeconomic explanatory variables that may influence environmental footprints: per capita GDP (PPP corrected; € • 1000), population density (PD; $n \cdot km^{-2} \cdot 1000$), and the Gini index (dimensionless between 0 [complete equality] and 1 [complete inequality]). GDP and population density have been shown to influence footprints in earlier work (Wilting, Schipper, Bakkenes, Meijer, & Huijbregts, 2017). We added the Gini index in order to test whether a region's footprint may change depending on income inequality. We retrieved the input data for the explanatory variables from Eurostat (2018) and the OECD (2018) (Table S2.2 in Supporting Information S2).

Prior to the regression analysis, we assessed the correlations among the explanatory variables with variance inflation factors (VIFs). All VIFs were below 3, indicating limited collinearity (Zuur, Ieno, Walker, Saveliev, & Smith, 2009). Further, we standardized the predictor variables (zero mean and unit variance) and we $\log_{10}$ transformed the per capita biodiversity footprints as these were positively skewed. We then fitted linear mixed effect models with country as random intercept term to account for possible systematic differences in footprints at the country level as well as unequal numbers of regions among countries. We included the squared terms of the explanatory variables to account for possible nonlinear relationships. To prevent overfitting, we performed stepwise variable selection to identify the most parsimonious model per footprint, using the Akaike Information Criterion (AIC), and allowing a quadratic term only if the corresponding linear term was also included. We assessed the importance of the selected variables by refitting each model using randomized values for the predictor variable of concern, calculating Pearson's correlation coefficient between the predictions of the model based on original and randomized data, and quantifying variable importance as 1 minus the correlation (Thuiller, Georges, Engler, & Breiner, 2016). We did this 100 times and averaged the importance over the 100 iterations (see also Section S1.5 in Supporting Information).

3 | RESULTS

3.1 | Subnational footprints

Our results revealed large differences in per capita GHG footprints between regions (Figure 1). Luxemburg, Cyprus, Hamburg, Åland, and two regions in Greece showed relatively high per capita GHG footprints with values of 19.6–24.6 metric ton CO₂-equivalents (Table S2.3 in Supporting Information S2). The lowest per capita footprints occurred in some of the Spanish regions (Valencia, Andalusia, and Catalonia), Romania and Bulgaria, with values of 5.7–7.2 metric ton CO₂-equivalents. The per capita land-based biodiversity footprints (measured as MSA-loss•ha) also revealed large differences between EU regions (Figure 1). All Finnish regions showed high per capita biodiversity footprints, with values of 1.5–2.0

Footprints in EU27, 2010

GHG footprint

Biodiversity footprint

FIGURE 1 Per capita GHG (left) and biodiversity (right) footprints of 162 EU regions (excluding Croatia), 2010. Note that Cyprus, the Canary Islands, and the Spanish enclaves in North-Africa fall outside the maps, but the results for these regions are included in Table S2.3 in Supporting Information S2. Underlying data used to create this figure can be found in Supporting Information S3

MSA-loss-ha (Table S2.3 in Supporting Information S2). High values (between 1.0 and 1.5 MSA-loss-ha) were also observed for Sweden, Latvia, Estonia, and the Greek region Ipeiros. The lowest per capita biodiversity footprints (below 0.35 MSA-loss-ha) were found in Malta, Spain (Valencia and the Canary Islands) and Campania and Liguria in southern Italy. Although the overall correlation between per capita GHG and biodiversity footprints was relatively small ($R^2 = 0.20$; Figure S2.1 in Supporting Information S2), the Finnish regions not only showed large biodiversity footprints, but also relatively large GHG footprints. The Spanish regions Valencia, Andalusia, and Catalonia showed small per capita GHG footprints in combination with small per capita biodiversity footprints. However, the Netherlands and several regions in Germany showed relatively large per capita GHG footprints in combination with small per capita biodiversity footprints. Contrarily, Latvia, Romania, Lithuania, and the Portuguese region Alentejo showed large biodiversity footprints while their GHG footprints were relatively small.

The 16 countries with more than one region in our analysis showed different levels of variability in their subnational GHG footprints. Spain, Germany, Italy, and Slovakia displayed the largest ranges in regional footprints within the country (Figure 2; Table S2.4 in Supporting Information S2). The large variability in Germany was mainly caused by Hamburg, which had a considerably higher per capita GHG footprint (21.2 metric ton CO₂-equivalents) than the other German federal states. Spain showed a factor of three difference between the largest (Extremadura) and the smallest per capita GHG footprint (Valencia). For biodiversity, Greece, Spain, and Finland showed the largest intra-country variability in the regional footprints (Figure 2; Table S2.4 in Supporting Information S2). Ita-Suomi was the region with the lowest per capita biodiversity footprint in Finland (1.5 MSA-loss-ha), yet it was higher than the per capita biodiversity footprints in all regions in the other countries. Ipeiros was an outlier within Greece with 1.3 MSA-loss-ha per capita. Spain showed the highest ratio between the largest and the smallest per capita biodiversity footprint. The per capita footprints of Aragon and Castile and León were almost a factor of 3.5 higher than the per capita biodiversity footprint of Valencia. Additional data on absolute and relative measures of variability, including ranges, interquartile ranges (IQRs), and the ratio between IQR and median, are available in Table S2.4 in Supporting Information S2.

3.2 | Footprints per final demand category and contributing sectors

On average, household consumption accounted for a considerably larger share of the GHG and land-based biodiversity footprints than government consumption and investments (Figure 3). Where the share of household consumption in total final demand (expenditures in

Variations in footprints in 16 EU countries, 2010

GHG footprint

Biodiversity footprint

FIGURE 2 Variation in the per capita GHG (left) and biodiversity footprints (right) over regions for the 16 EU countries with more than one region in our analysis, 2010. Boxes show the first and third quartiles (25–75%), and whiskers show the ranges per country. Underlying data used to create this figure can be found in Supporting Information S3

Contribution of final demand categories to final demand and footprints, EU27, 2010

Final demand

GHG footprint

Biodiversity footprint

FIGURE 3 Contributions of three final demand categories to total consumption (left), GHG (center), and biodiversity (right) footprints, 2010. Boxes show the first and third quartiles (25–75%), and whiskers show the ranges for 162 regions. Underlying data used to create this figure can be found in Supporting Information S3

euros) was between 55% and 60%, the share of household consumption in the GHG footprint, including direct emissions, was typically between 70% and 80%. For most regions, the share of household consumption was even higher for the land-based biodiversity footprint (80–90%).

The differences in shares of the final demand categories in total footprints reflect the differences in sectors contributing to final demand (Figure 4). The GHG emissions from EU household consumption were dominated by energy consumption, including direct emissions from households related to the use of energy at home and in private cars. Furthermore, the land-related impacts on biodiversity from household consumption were mainly related to demands for agricultural products and food (50%). Demand for these products is less important in government consumption and investments. Government consumption consisted for more than 90% of non-market services that have relatively small GHG emissions and

Breakdown of final demand and footprints per category and sector, EU27, 2010

FIGURE 4 Contribution of sectors to three final demand categories measured as expenditures (left), GHG footprints (center), and biodiversity (right) footprints, 2010. Shares are based on the totals over all 162 EU regions. Underlying data used to create this figure can be found in Supporting Information S3

biodiversity losses per euro consumed. Investments that mainly consisted of demand for manufacturing (including construction), such as demand for machines, vehicles, and buildings, showed on average a higher share in the GHG footprint than in the biodiversity footprint. For further details on the contributions of sectors to the footprints per region we refer to Table S2.3 in Supporting Information S2.

3.3 | Trade in GHG emissions and impacts on biodiversity

For 88% of the EU regions (143 out of 162), more than half of the GHG footprint was caused by GHG emissions outside their territory (Table S2.3 in Supporting Information S2). The GHG footprints in the regions Åland and several regions in Italy and Spain were particularly dominated by trade, with imports accounting for more than 80% of the total footprint. Only for some countries, including Estonia, Romania, Bulgaria, Scotland, Slovenia, Latvia and Cyprus, the Spanish region Valencia, South and Eastern Ireland, and several regions in Poland, the trade share of their GHG footprint was less than 50%. For 103 regions, the share of the foreign GHG emissions that occurred in other EU regions was larger than the share of the foreign emissions outside the EU (Figure 5). Clear exceptions were the Finnish regions, which showed more than 40% of their consumption-related GHG emissions outside the EU, with a share of emissions in Russia of around 15% of the total.

For 71% of the EU regions (115 of the 162), more than half of their land-based biodiversity footprint originated outside their territory (Table S2.3 in Supporting Information S2). The larger countries Romania and Bulgaria, but also the Baltic states, the Greek region Ipeiros and Castilla y Leon in Spain, showed foreign shares below 30% and hence domestic shares above 70%. For 129 regions, biodiversity losses imported

GHG footprint foreign share

Rest of EU27

Rest of the world

Foreign share (%)

Biodiversity footprint foreign share

Rest of EU27

Rest of the world

Foreign share (%)

FIGURE 5 Foreign shares, divided in rest of the EU27 (left) and rest of the world (right), in GHG (top) and biodiversity footprints (down) for 162 EU regions (excluding Croatia), 2010. Note that Cyprus, the Canary Islands, and the Spanish enclaves in North-Africa fall outside the maps, but the results for these regions are included in Table S2.3 in Supporting Information S2. Underlying data used to create this figure can be found in Supporting Information S3

from other EU regions were larger than losses imported from outside the EU (Figure 5). For all three Belgium regions, Luxembourg, and the Netherlands, more than half of the consumption-related biodiversity losses occurred outside the EU.

The 16 countries with more than one region in our analysis showed different levels of variability in their subnational trade shares (Figure 5). Spain and Italy displayed the largest ranges in the shares of regions outside the EU in their GHG and biodiversity footprints (Table S2.5 in Supporting Information S2). The United Kingdom, Greece, and Finland also showed large ranges in the outside-EU shares in the biodiversity footprints. We split up the shares of the foreign footprints in EU regions in regions in the same country and EU regions outside the country. This revealed high variability especially in the share of the other regions in the same country in the subnational GHG and biodiversity footprints (Table S2.5 in Supporting Information S2). For Italy, for instance, the range in the share of other regions in the same country in the GHG and biodiversity footprints was 11–44% and 5–50%, respectively. Sardinia, being relatively isolated from the rest of Italy, showed small shares of other Italian regions in its footprints compared to the other Italian regions.

3.4 | Relationships between footprints and explanatory variables

Overall, variability in footprints was mostly explained by the country-level random intercept, as revealed by both the variable importance assessment (Figure 6) and the differences between marginal and conditional R^2 values (Table 1). The total per capita GHG footprint was further related to GDP per capita, with increasing per capita GDP associated with increasing footprints (Figure 6; Table 1). Both the domestic and the foreign GHG footprint increased with income, yet the increase was larger for the footprint exerted abroad. The Gini coefficient was a significant explanatory variable as well, whereby the negative relationship indicates that the total per capita GHG footprint increases with income equality.

By contrast, we found no evidence that the total per capita land-based biodiversity footprint is related to per capita GDP or income equality (Figure 6; Table 1). The domestic and foreign footprints showed, however, a more detailed picture (Figure 6; Table 1). We found that an increase in income coincides with a decrease in the domestic biodiversity footprint yet an increase in the biodiversity footprint exerted abroad. Similar relationships were found for population density, indicating that more densely populated regions import more biodiversity loss.

For none of the footprints, the most parsimonious model included a quadratic term for per capita GDP or Gini index, indicating no nonlinearities in the relationships. We found a quadratic term only for population density in the regression models for the domestic and foreign biodiversity footprints, indicating a levelling off of the response.

4 | DISCUSSION

4.1 | Sectoral detail

As far as we know, this is the first study that investigates environmental footprints at the EU subnational level by employing a full EEMRIO model including subnational trade flows. Where several MRIO databases with all their specific sector and region classifications are available for national footprint studies, detailed subnational tables covering the EU are scarce. The subnational MRIO table that we used as a starting point, EUREGIO, distinguishes only 14 sectors. By disaggregating the agricultural sector into five subsectors, we managed to expand to 18 sectors. This number is still below the around 40 sectors as recommended by Su, Huang, Ang, and Zhou (2010) in their study on the effects of sector aggregation on CO₂ emissions embodied in China's and Singapore's exports. Several other studies on GHG emissions embodied in trade or CO₂ multipliers show that aggregation to a relatively small number of sectors leads to significant errors (Lenzen, Pade, & Munksgaard, 2004; Steen-Olsen, Owen, Hertwich, & Lenzen, 2014; Wyckoff & Roop, 1994). We did not find any analyses of the effect of sector aggregation on estimates for land-based biodiversity footprints, but studies on raw material footprints revealed that the aggregation bias was highest for agricultural and mining sectors (de Koning et al., 2015; Piñero, Heikkinen, Mäenpää, & Pongrácz, 2015). In this context our disaggregation of the agricultural sector was a step in the right direction, but EUREGIO includes other heterogeneous sectors that are relevant to disaggregate, such as the energy and mining sector, which we could not disaggregate here by lack of disaggregated subnational production data.

In order to increase the robustness of our results more detailed tables are required. Subnational MRIO tables for the EU with more detail in regions and sectors are underway (Thissen, Ivanova, Mandras, & Husby, 2018), but were not available at the moment of analysis. Furthermore, these tables still lack the detail in agricultural subsectors that is required for calculating land-based biodiversity footprints. As detailing procedures developed for global MRIO databases, such as EXIOBASE, can be used to disaggregate official MRIO tables to more detailed levels as suggested by Tukker et al. (2018), they could be useful for disaggregating subnational MRIO tables as well.

Importance of explanatory variables for per-capita footprints

FIGURE 6 Importance of the explanatory variables for the total, domestic, and foreign per capita GHG (top) and biodiversity footprints (down) based on the most parsimonious regression models, as based on Akaike Information Criterion (AIC). PD, population density; GDP, per capita gross domestic product; GINI, Gini index. Underlying data used to create this figure can be found in Supporting Information S3

4.2 | Subnational footprints

A comparison of the per capita household GHG footprints calculated in this study with those in Ivanova et al. (2017), shows that our values are on average 19% lower (unweighted average of per capita footprints in all regions). Only for Hungary they are at the same level. Our per capita household GHG footprints of the German federal states are also lower than the values reported by Miehe et al. (2016). Similarly, our per capita household GHG footprint of Flanders (Belgium) was with 11.4 metric ton CO₂-equivalents significantly lower than the value of 14.0 metric ton CO₂-equivalents reported by Christis, Breemersch, Vercalsteren, and Dils (2019). Both the MRIO databases used and the choice of the base year appear to be important explanations for the differences found. Where we based our calculations on EUREGIO with 2010 data, that is, after the 2008 economic crisis, Ivanova et al. (2017) and Christis et al. (2019) used EXIOBASE, version 2.3 with 2007 data, and Miehe et al. (2016) used data based on GTAP, version 7, with data for 2004. Differences in footprints at the national level are often explained by differences in the MRIO databases used (Owen, Wood, Barrett, & Evans, 2016). Furthermore, the Global Carbon Atlas (Global Carbon Project, 2019) shows a decline in the per capita CO₂

TABLE 1 Coefficients (standardized) and variance explained of the most parsimonious regression models, as based on Akaike Information Criterion (AIC), relating per capita GHG and land-based biodiversity footprints to socioeconomic explanatory variables: Population density (PD), per capita gross domestic production (GDP), and the Gini index (as measure for income inequality). Significance codes include *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Model characteristic	GHG			Biodiversity		
	Total	Domestic	Foreign	Total	Domestic	Foreign
<i>Explanatory variable</i>						
Country (random intercept)	12.60(±0.56)***	5.39(±0.37)***	7.25(±0.37)***	−2.21(±0.03)***	−2.68(±0.06)***	−2.50(±0.03)***
PD	–	−0.21(±0.09)*	–	–	−0.24(±0.04)***	0.08(±0.02)**
PD ²	–	–	–	–	0.03(±0.01)***	−0.01(±0.00)**
GDP	1.76(±0.16)***	0.74(±0.11)***	1.18(±0.15)***	–	−0.04(±0.02)*	0.05(±0.01)***
Gini index	−0.77(±0.17)***	–	−0.65(±0.16)***	–	–	–
<i>Variance explained</i>						
Marginal R ²	0.28	0.10	0.27	0.00	0.12	0.14
Conditional R ²	0.84	0.82	0.71	0.83	0.80	0.77

“–” variable was not included in the most parsimonious regression model for the corresponding footprint.

footprint in the EU of 2.7% annually between 2005 and 2010, which is in line with our findings. However, the large value that we found for Hamburg was not supported by these studies, but is the result of the large per capita consumption figure for this region in the EUREGIO database.

The high values for the per capita land-based biodiversity footprint of the Finish regions, Sweden, the Baltic states, and Luxembourg are in line with Lugschitz, Bruckner, and Giljum (2011), who reported high per capita land footprints for these countries. More than a quarter of the biodiversity footprints of the Finish regions, Sweden, and Estonia are from the use of forestry land. Furthermore, the large infrastructure-related MSA values for Finland, Sweden, and the Baltic States, resulting from roads as the only driver of biodiversity losses in natural areas, contributed to the high per capita biodiversity footprints in these countries.

MSA is a so-called intactness indicator, measuring the degree to which community composition resembles an undisturbed situation. As MSA does not account for spatial differences in species richness, it is less suitable to capture different implications of consumption between species-rich and species-poor regions (Marquardt et al., 2019). Therefore, it would be useful to investigate subnational biodiversity footprints based on other biodiversity indicators with different characteristics, such as the vulnerability-weighted global relative species richness indicator (Marquardt et al., 2019) or metrics based on threatened species (Lenzen et al., 2012), in order to obtain a more complete and robust overview of the impacts of consumption on biodiversity.

4.3 | Subnational differences

In our study, the variation in subnational footprints within a country results from differences in household consumption patterns as well as structures of regional production and interregional trade, and in case of the biodiversity footprints also subnational differences in direct land-use intensities. We found similar levels of variability in GHG footprints as Ivanova et al. (2017), who did not use subnational data on trade and production structures. Yet, Ivanova et al. (2017) included more details in consumption patterns (200 products vs. 18 sectors in our study), which may have increased the variability. Both studies revealed the same countries, viz. Italy, Spain, and Slovakia, with the largest variability among regions. The variation that we found for Germany, with relatively small GHG footprints for eastern Germany and a relatively high footprint for Bavaria, is in line with the findings of Mieke et al. (2016).

In an additional analysis (as described in Section S1.6 in Supporting Information), we excluded the subnational data on production, trade and, in case of biodiversity, land use from the calculation of the footprints in order to determine the contribution of the subnational data to the variation in the footprints. This exclusion resulted in considerably reduced variability in the land-based biodiversity footprints compared to the results based on subnational data (Table S2.6 in Supporting Information S2), whereas the variability in GHG footprints remained similar. This difference seems to reflect the use of subnational land-use data in calculating the biodiversity footprint versus the use of national GHG data in calculating the GHG footprint. It would be worth to verify this once subnational GHG emission data become available.

The use of national sectoral direct GHG intensities for all regions in a country may introduce uncertainties to the final results because of possible different energy structures across countries, particularly in combination with the aggregated sector detail in our model. For example, the extraction of crude petroleum and natural gas in some regions of a country and the mining of metals or industrial minerals in other regions are both represented in the same sector (mining, quarrying, and energy supply). The use of national intensities in these cases would probably be inconsistent. Therefore,

we recommend to include subnational intensities in regional footprint modeling where possible. A possible way to derive subnational intensities is to start from a spatially detailed emission inventory, such as the TNO-MACC_II emission inventory (Kuenen, Visschedijk, Jozwicka, & Denier van der Gon, 2014), and to allocate to subnational regions based on spatial overlay. An additional step is required then to transform the territorial-based emissions into production-based emissions, which is a step that can be quite challenging for emissions from transport. When complete databases for all regions are not available an alternative might be to derive subnational intensities for some defined regions or sectors by combining subnational production data, such as the AGRESTE data set in France for detailed information on agricultural production (AGRESTE, 2020), and emissions factors by applying the procedure described by Merciai and Schmidt (2018) for the construction of the EXIOBASE 3 hybrid database.

4.4 | Final demand categories and contributing sectors

The share of household consumption in the GHG footprints was on average 75% (Figure 3), indicating that studies focusing on household expenditures cover the main part of national and subnational GHG footprints. Our findings are in line with those of Hertwich and Peters (2009) who found that 72% of the global GHG emissions are related to household consumption, 10% to government consumption, and 18% to investments. For 160 regions, the share of household consumption was even higher in the land-based biodiversity footprints than in the GHG footprints (Table S2.3 in Supporting Information S2). This finding is in line with Ivanova et al. (2016) who reported average shares of household consumption of 70% in the land footprint and 65% in the carbon footprints based on 43 countries and regions worldwide.

The subnational final demand structures in the EUREGIO table are based on national demand structures (Thissen et al., 2018). We adjusted the household consumption structures based on Ivanova et al. (2017), but did not change the structures of government consumption and investments by lack of appropriate data. National government consumption is dominated by non-market services and we do not expect that this is different at the subnational level. Investments are mainly produced by manufacturing including construction (Figure 4), but regional differences are conceivable. Given the relatively low supply-chain GHG emissions and biodiversity losses of manufacturing and construction, however, we expect that differences in the subnational structures of investments will have a limited impact on the overall footprint results.

4.5 | Domestic and foreign shares

For almost 90% of the regions, the foreign part of the GHG footprint was higher than the domestic part. As these were mostly regions within wealthy countries, our results are in line with the findings of Davis and Caldeira (2010), who concluded that wealthy countries, such as France, Sweden, the United Kingdom, and Austria, are primary importers of consumption-based emissions. These are typical service economies with relatively efficient energy production and limited natural resources. Furthermore, for subnational regions, foreign emissions also include emissions in other regions in the same country, which are all domestic in a national approach. Only for some individual countries, including Romania, Estonia, Bulgaria, Malta, Slovenia and Latvia, and several regions in Poland, the share of their domestic GHG footprint was above 50% as a result of relatively high demand from GHG-intensive domestic production sectors, including energy supply and transport. Our finding that 71% of the regions displace more than half of their biodiversity footprint to other regions, including other regions within the same country, is consistent with studies on the tele-connection between local consumption and global land use (Chen & Han, 2015; Yu, Feng, & Hubacek, 2013). The larger countries Romania, Bulgaria, and Sweden, but also the Baltic states and Pohjois-Suomi in Finland, showed foreign shares below 25% (hence domestic shares above 75%). Especially, the northern regions, which have a relatively high demand for forestry, show a high rate of self-sufficiency in their wood consumption. Romania and Bulgaria are relatively self-sufficient in their food supply.

4.6 | Socioeconomic drivers

Our results revealed that GHG emissions and biodiversity losses are not equally distributed. Rich regions with high income equality have relatively high per capita GHG footprints. The strong relationship between income and consumption-based GHG emissions was found before at the level of nations (Davis & Caldeira, 2010; Hertwich & Peters, 2009). Furthermore, the high explanatory power of income was also found for the subnational household GHG footprints within the EU as presented by Ivanova et al. (2017). Our finding that subnational regions with higher income equality (measured by the Gini coefficient) have higher per capita GHG footprints is in line with the finding by Golley and Meng (2012) that more equal incomes lead to higher GHG footprints, as reported for households in Chinese urban areas. Similarly, Jorgenson (2003) found a positive relationship between per capita ecological footprints and domestic income equality. He stated that within countries with higher income inequality, a larger proportion of a nation's annual income is generally accounted for by a small part of the domestic population, while the majority of the population has substantially lower income levels. When the income distribution becomes more equal (at the same given average income) the additional expenditures of the lower incomes might be more GHG intensive than the expenditures given up by the higher incomes. This is in line with studies that found

that the GHG intensity of consumption decreases with rising expenditures (GHG elasticity of expenditures is below 1) (Hertwich & Peters, 2009; Ivanova et al., 2016). Further research on differences in consumption patterns and the related GHG footprints in regions with the same average income, but different levels of income equality is required to verify our results.

We did not find a strong relationship between the per capita GHG footprint and human population density. This is in line with Ivanova et al. (2017), who found no relationship with population density for the overall GHG footprint of households either, but just for expenditures on mobility. The latter was confirmed by Ivanova et al. (2018) showing that population density decreases emissions associated with housing and car travel. Furthermore, Gill and Moeller (2018) showed for German households that per capita GHG emissions in rural and urban areas are more or less at the same level, even though rural households have higher shares of emissions from direct energy use in their consumption patterns. Their results showed that the density effect of cities saves GHG emissions, but smaller household sizes, higher incomes, and greater consumption opportunities in cities work in the opposite direction.

Our regression analysis did not reveal significant relationships between a region's total per capita biodiversity footprint and income, income equality, or population density. This is in contrast with previous studies reporting positive correlations between land-based footprints and income (Marques et al., 2019; Weinzettel, Hertwich, Peters, Steen-Olsen, & Galli, 2013). However, these studies are global studies including both developing and developed countries, hence a large gradient in incomes, where our study is confined to regions within a relatively wealthy continent. The smaller gradient in income may also explain why we did not find a quadratic term for per capita income in the regression models for the GHG footprints. In their global study, Wilting et al. (2017) showed a slight increase in the land-based biodiversity footprint with increasing income, but this was small compared to the income-related increase in GHG footprints. Koslowski et al. (2020) found that per capita biodiversity footprints in Europe increased with per capita GDP, but their biodiversity footprints were not only land related, but also included other pressures, such as GHG emissions. Extra income is primarily spent on mobility and other energy-intensive activities rather than on land-intensive activities, such as food. Our regression analysis further showed a shift of the land-based biodiversity footprint to other regions (especially in other continents) when population density and income rise. Regions with a high population density showed a small domestic land-based biodiversity footprint indicating that these regions do not have enough land to fulfil their land-related consumption needs. These regions included urban regions, such as Brussels, Hovedstaden region (Copenhagen), London, Hamburg, and Berlin, but also densely populated countries, such as Malta, the Netherlands, and Luxembourg.

5 | CONCLUSIONS

The main objective of this study was to obtain more insights into within-country differences in GHG emissions and land-based biodiversity losses associated with final consumption in the EU. We built on previous studies on GHG footprints of subnational EU regions by extending household footprints to full subnational footprints, including government consumption and investments. Furthermore, we included region-specific data from MRIO databases on production and interregional trade flows in calculating the subnational footprints and next to that region-specific land-use data in calculating the land-based biodiversity footprints. Our study revealed that the contribution of government consumption and investments to the GHG and biodiversity footprints was substantial in most of the regions, although household consumption remained by far the largest contributor, with EU averages of 75% and 87%, respectively. The use of subnational information about production and trade structures did not lead to higher variation in the GHG footprints within a country compared to footprints calculated with national intensities. Hence, the variation in GHG footprints was mainly the result from subnational differences in final demand. The variations in the per capita land-based biodiversity footprints among regions within a country, however, were lower when excluding subnational data from the calculations, possibly reflecting an effect of subnational information on land use. We found a positive relationship between the per capita GHG and biodiversity footprints with an explained variance of about 20%. This means that the two indicators have added value against each other, as the unexplained variance of the relationship was 80%.

Regional policies to mitigate GHG emissions and to avert biodiversity losses now primarily focus on territorial pressures and impacts. Insights from subnational footprint studies as ours can help regional policymakers to take into account environmental pressures and impacts from a consumption-based perspective and to consider reduction measures tailored to consumption, production, and trade within the region, which may differ from the national patterns. The variation found in the per capita GHG and biodiversity footprints among regions within the same country may help national policymakers to take into account regional differences in implementing policy instruments, such as eco-taxes on products or carbon caps, at the national level in an effective, efficient, and fair way.

The within-country variation in environmental footprints and the potential use in subnational and national policies justifies further investigation into subnational footprints in EU countries. Where we mainly used existing data sets for our analysis, we ran into a number of limitations as discussed above. To increase the robustness of subnational footprint results for policy use, we recommend further data development, with the compilation of subnational MRIO databases, including more sectoral details and harmonized environmental data, as the most important step. The directions and ways we have described for data creation and improvement can help with this.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGMENTS

The authors thank Mark Thissen (PBL) for his help with interpreting the EUREGIO database and Mirza Čengić (Radboud University) for his help with the variable importance calculations. Furthermore, the authors thank Durk Nijdam and Sandy van Tol (PBL) for the preparation of figures and maps. Finally, the authors would like to thank the editor Richard Wood and three anonymous reviewers for their constructive comments and useful suggestions for improving the article.

ORCID

Harry C. Wilting <https://orcid.org/0000-0002-2330-8820>

Diana Ivanova <https://orcid.org/0000-0002-3890-481X>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Wilting HC, Schipper AM, Ivanova O, Ivanova D, Huijbregts MAJ. Subnational greenhouse gas and land-based biodiversity footprints in the European Union. *J Ind Ecol*. 2020;1–16. <https://doi.org/10.1111/jiec.13042>