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Affluence drives the global displacement of land use

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ABSTRACT

Increasing affluence is often postulated as a main driver for the human footprint on biologically productive areas, identified among the main causes of biodiversity loss, but causal relationships are obscured by international trade. Here, we trace the use of land and ocean area through international supply chains to final consumption, modeling agricultural, food, and forestry products on a high level of resolution while also including the land requirements of manufactured goods and services. In 2004, high-income countries required more biologically productive land per capita than low-income countries, but this connection could only be identified when land used to produce internationally traded products was taken into account, because higher-income countries tend to displace a larger fraction of land use. The equivalent land and ocean area footprint of nations increased by a third for each doubling of income, with all variables analyzed on a per capita basis. This increase came largely from imports, which increased proportionally to income. Export depended mostly on the capacity of countries to produce useful biomass, the biocapacity. Our analysis clearly shows that countries with a high biocapacity per capita tend to spare more land for nature. Biocapacity per capita can be increased through more intensive production or by reducing population density. The net displacement of land use from high-income to low-income countries amounted to 6% of the global land demand, even though high-income countries had more land available per capita than low-income countries. In particular, Europe and Japan placed high pressure on ecosystems in lower-income countries.

1. Introduction

The increasing human demand for biologically productive land and ocean area to provide food, fiber, fuels, and construction materials limits humanity's ability to preserve biodiversity (Butchart et al., 2010; Defries et al., 2010; Foley et al., 2005, 2011; Godfray et al., 2010; Lambin and Meyfroidt, 2011; Pauly et al., 2002; Tilman et al., 2009; Wirsenius et al., 2010). Population growth and a change to more affluent diets including higher meat and dairy consumption result in the need to expand or intensify agricultural and forestry production (Foley et al., 2011; Godfray et al., 2010; Kastner et al., 2012). The additional inputs required to intensify production, including fossil energy (Erb et al., 2008), nitrogen (Tilman et al., 2011), phosphorus (Cordell et al., 2009), and fresh water (Pfister et al., 2011), are themselves in limited supply and their use leads to ecosystem impacts (Foley et al., 2005, 2011). Additional requirements for land use come from the increased demand for bioenergy and biomaterials as part of climate change mitigation initiatives (Tilman et al., 2009). Land is also being lost in some areas due to desertification or encroaching human settlements, while in other areas, climate change leads to increased biological productivity (Fischlin et al., 2007).

Despite the increasing competition for biologically productive land, the current pattern of biomass use and its drivers are not fully understood. Studies have systematically addressed food production and forestry, but often separately, and rarely include fisheries and settlement areas. Investigations of per-capita consumption of food, particularly animal products, indicate a steady increase of consumption with increased income (Myers and Kent, 2003; Tilman et al., 2011), while historical studies indicate a decoupling of total biomass use from economic development (Krausmann et al., 2009) and contemporary cross-sectional analyses show no correlation of biomass use and income (Steinberger and Krausmann, 2011). One explanation for the lack of coupling of biomass use to development is the historical replacement of biomass use for energy purposes (draught animals, firewood) with fossil fuels (Krausmann et al., 2009); another is the displacement of land use to other countries through the increased import of food and forestry products by rich countries (Erb et al., 2009; Lambin and Meyfroidt, 2011; Mayer et al., 2005; Rudel et al., 2009). The term

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displaced land use refers to the land use abroad caused by consumption originating from the country in question. Conversely, the foreign countries *absorb* land use, which is the land use inside a country for production of goods consumed abroad (Meyfroidt et al., 2010).

The objective of this study is to better understand the utilization of land by humans, including biomass derived from this land, for final consumption, as a function of affluence and resource endowment, taking into account production chains and international trade. As such, it aims to provide insight into the drivers of land use. The work is based on a novel hybrid input–output model that models land use as well as the production of and trade in agricultural and forestry products in physical terms while also considering these parameters in the manufacture of other commodities based on a global multiregional input–output model. We identified the displacement of land use through the international trade in primary and manufactured products as well as services and calculated the resulting national land footprints. We then tested in a cross-national analysis whether income, the availability of bioproductive land (biocapacity), and country size (as a proxy for the need to trade internationally) could explain the displacement and absorption of land use, the total land footprint, or the domestic land use for production.

2. Materials and methods

The analysis of land utilization by humans for production and consumption is based on the following elements:

(1) Land use and the production of and trade in primary agricultural and forestry products was based on data from the Food and Agricultural Organization of the United Nations (FAO, 2010).

(2) The actual land and ocean area utilized by humans was weighted according to its current productivity of usable biomass products, i.e. products of economic interest to people (Wackernagel et al., 2002), by converting it into an equivalent area of global average productivity (Ewing et al., 2010), measured in global hectares (gha), similar to the Ecological Footprint (Wackernagel et al., 2002). We adopted the term "land footprint" to describe the equivalent land use required to satisfy consumption.

(3) The use of primary agricultural and forestry products by economic sectors such as the manufacture of food products or furniture, and the use of land by sectors such as road transport was quantified based on several data sources documented in (Weinzettel et al., 2011). The Global Trade Analysis Project's classification of a national economy in terms of 57 sectors was used. The resulting environmental extensions to the GTAP-based multiregional input–output (MRIO) model (Peters et al., 2011a; Weinzettel et al., 2011) trace the use of land and biomass by the world economy. The construction of these extensions is documented in Weinzettel et al. (2011).

(4) The MRIO model utilized was constructed based on the GTAP v.7 data (Narayanan and Walmsley, 2008) and describes 94 individual countries and 19 'rest of' regions. The construction is described in Peters et al. (2011a).

(5) The linear algebra of a Leontief-type demand-pull input–output model was used to calculate the global production activity required to satisfy final demand in each country and to quantify the resulting biomass input and associated equivalent land use. The modeling is similar to the analysis of CO_2 embodied in trade (Peters et al., 2011b), but the more detailed extensions allow us to trace traded agricultural commodities in the more detailed classification of the FAO database. The model results describe the land footprint of final consumption of each country in terms of land type (cropland, pasture land, forestry land, marine land and built-up land) and country in which the land use happens. The results were aggregated to describe the land footprint of consumption, the displaced land use and absorbed land use.

(6) Multivariate regression analyses were conducted to establish potential relationships between dependent variables related to land-use, all described in per-capita terms, and independent variables. The dependent variables investigated were land footprint, displaced land use, absorbed land use, land use for production, and net displaced land use. The independent variables were per-capita GDP adjusted by purchasing power parity, per-capita domestically available bioproductive land area (biocapacity), reflecting the potential biomass production, and total land area of a country, reflecting the opportunity to trade with other countries. Analyses were conducted for both log-transformed variables and linear variables, except for net trade where a log-transformation of negative numbers was not possible. The least significant independent variable was eliminated from each regression, resulting in a bivariate regression analysis.

The supplementary data include more information on the data sources and conversions, the MRIO modeling, and the regression analysis, including a representation of the correlations between independent variables.

3. Results

3.1. Land use connected to consumption vs. production

The amount of biologically productive land required to satisfy the consumption per average inhabitant (land footprint per capita) varied widely across countries, from 0.4 gha/person (gha/p) for Bangladesh and Pakistan to 5.8 gha/p for Finland and 6.7 gha/p for Norway (Fig. S1). The most important countries in terms of total land footprint were the United States (13% of the global total; 3.5 gha/p), China (12%; 0.77 gha/p), and India (8%; 0.55 gha/p). The European Union's land footprint was 2.5 gha/p (16% of global total), compared to a global average of 1.2 gha/p and a global average per capita biocapacity of 1.8 gha/p (Fig. 1). The composition of individual land use types shows that land use for agriculture and

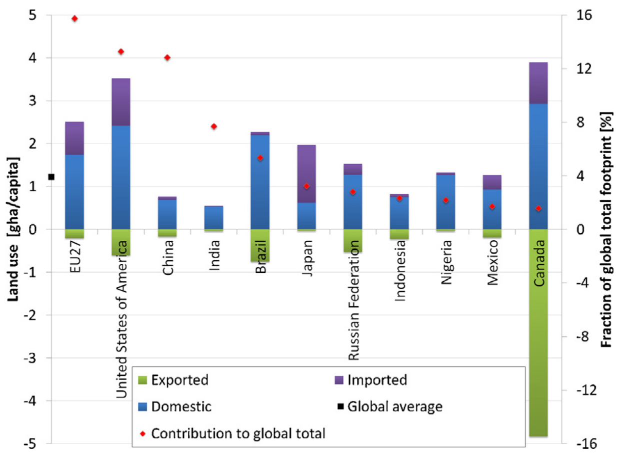

Fig. 1. Use of biologically productive land per capita in the EU27 and the 10 countries with the highest total land footprint. A region's footprint consists of a domestic component as well as an imported component – the land use displaced to other countries through imports. The total land use in a country equals the domestic component of its footprint plus land use absorbed through exports. The countries' contribution to the global total refers to the right axis.

Table 1
Results of the multivariate regression analysis of the per capita equivalent land use of countries related to their consumption (land use footprint), imports (displaced land use), exports (absorbed land use), and production (domestic land use). The general form of the regression equation is $F = kA^{\alpha}S^{\gamma}$ for import and $F = kA^{\alpha}S^{\beta}$ for production, export and consumption, with affluence *A* (GDP per capita in purchaser power parity), availability of biologically productive land *B* (gha/capita), and surface area *S* (km^2). The correlations between the dependent variables (*A*, *B*, and *S*) are presented in Table S4. *n* represents the number of countries that have all the data available for the regression analysis.

Measure	*n*	r^2	*F*-statistics	*p*-value	Affluence (α)	Biocapacity (β)	Surface area (γ)
Production	88	0.83***	212	$<10^{-4}$	0.07 ± 0.07	**0.7 ± 0.1**	n.s.
Export	88	0.73***	117	$<10^{-4}$	0.38 ± 0.14	**1 ± 0.2**	n.s.
Consumption	88	0.77***	141	$<10^{-4}$	**0.35 ± 0.06**	0.23 ± 0.06	n.s.
Import	91	0.90***	406	$<10^{-4}$	**1.0 ± 0.1**	n.s.	−0.3 ± 0.1

*** $p < 0.001$.

forestry were the most important land use types providing mainly food products and products associated to shelter (Fig. S1). The very high footprint of some smaller countries is explained by the high consumption of fish (Norway) and forestry products (Finland), see Fig. S1. The contribution of livestock varied between 0.04 (Sri Lanka) and 2.2 gha/p (Australia), with an average of 0.3 gha/p. 28% of cropland was used for livestock, which is broadly consistent with Foley et al. (2011). Pasture accounted for 0.14 gha/p or 12% of the land footprint of humanity. (See Fig. S2 and dataset.xls in the online supporting information for more country-level detail.)

The per capita land footprint is well explained by income and biocapacity (Table 1 and Fig. 2). The income and biocapacity elasticities of land footprint indicate that for each doubling of income, the land footprint increased by 35%; for each doubling of biocapacity, the footprint increased by 23%. The results of the land footprint analysis for consumption, however, contrast with the results of the analysis of biologically productive land and ocean area used for production, which are weakly correlated with income and strongly correlated with biocapacity (Table 1). The difference between this production perspective and the consumption perspective arises through land use displaced through international trade.

3.2. Land footprint of trade

The land footprint displaced through international trade was significant on a global level, corresponding to 1.8 billion gha or 24% of the global land footprint in 2004. The net displacement through trade from high-income countries (defined here as OECD member states as of 2011) to lower-income countries (non-OECD members) corresponded to 6% of total global land footprint or 25% of the total footprint associated with internationally traded products. This displacement happened despite the fact that OECD countries, on average, have a higher per capita biocapacity than non-OECD countries (3.0 vs. 1.6 gha/p). The robustness of the reported net displacement of land use from high-income to low-income countries with respect to the definition of high income was investigated. Using purchasing power parity adjusted gross domestic product per capita (GDP-PPP/p) as an indicator for income, we varied the definition of a high income from USD10,000 to 25,000. Across this range, the net displacement from high-income to low income countries is quite stable, at 5.3–6.4% of the total global land footprint and peaking at $20,000.

A more detailed understanding of the global trade patterns can be gained from investigating traded footprints per capita in

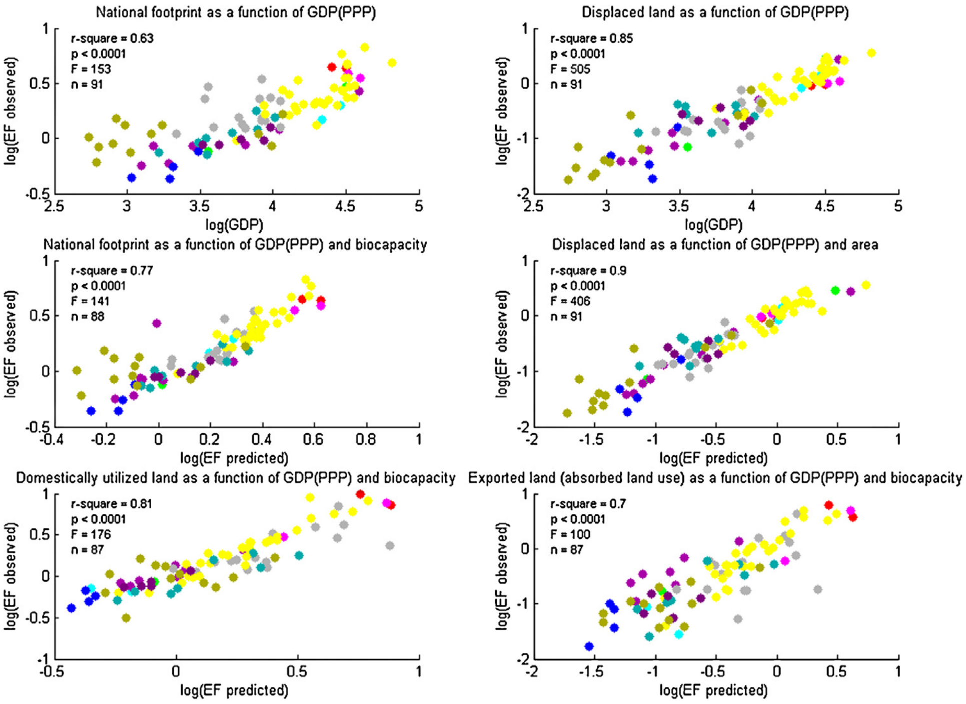

Fig. 2. Regression plots of per capita land footprint and displaced footprint of nations as a function of per capita GDP (top panels) and an additional variable (middle and bottom panels). The colors represent Sub-Saharan Africa (🟫), South Asia (🟦), South-East Asia (🟪), Latin America and Caribbean (⬜), OECD Europe (🟨), North America (🟪), Australia and New Zealand (🟥), Middle East and North Africa (🟪), Former Soviet Union (🟦), China (🟩), and South Korea and Japan (🟦). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

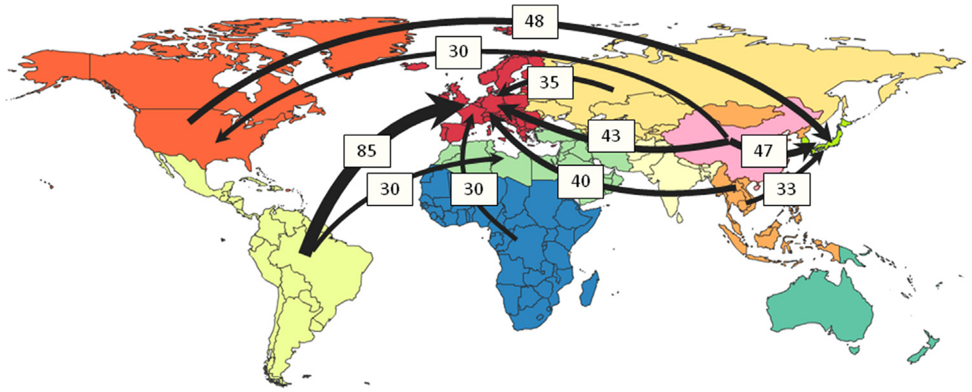

Fig. 3. Top ten net displacements of land use globally (exports minus imports), with the arrows indicating the direction of product flow. For this trade analysis, the countries of the world were aggregated into 11 regions, color coded on the map. Units are in million gha per year. The gross trade flows displayed in Fig. S2 show a substantial trade between North and South America. The definition of the regions is provided in the "dataset.xls" file, sheet "trade regions". (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

relation to biocapacity per capita, income per capita, and country size. The regression analysis indicates that the land use displaced through trade, that is, the land use required for imports, varied proportionally with income (elasticity = 1) and was inversely related to country size (Table 1); small and high-income countries would import relatively more. Moreover, domestic land availability (high per-capita biocapacity) did not reduce the displacement of land through imports, but rather increased exports. The footprint of exports was proportional to biocapacity and increased, albeit less strongly, with income. As expected, high-income countries trade more, but land use connected to imports increases faster with income than that connected to exports. The displaced fraction of land footprint hence also increases with income. The densely populated, industrialized economies of Europe, Japan, and Korea caused the largest net demand on foreign land, predominantly to medium-income countries in Latin America, China, and Southeast Asia (Fig. 3). The biggest gross exporters of land were China, USA, Canada, and Brazil while the biggest gross importers were USA, Japan, Germany, and China (Fig. S2 and Table S3). For a more detailed analysis of the EU countries' land footprints, as well as their internal and external displacement of land use, see Steen-Olsen et al. (2012).

4. Discussion

4.1. Biomass use increases with income

Our results provide strong support for the hypothesis that biomass use increases with affluence, but that this is not necessarily readily apparent because of international trade (Erb et al., 2009; Lambin and Meyfroidt, 2011; Mayer et al., 2005; Rudel et al., 2009). The cross-national analysis by Steinberger and Krausmann (2011), which shows no dependence of biomass use on income, was based on apparent consumption and thus accounted for the import and export of biomass in kg but did not consider biomass waste and inputs connected to the production of traded biomass. A similar approach was also taken in the time series analysis (Krausmann et al., 2009). The differing results can only be reconciled if there is a significant land footprint per unit traded biomass, where some biomass from the land may end up as waste or a low-value by-products or may be concentrated through livestock.

4.2. Land conservation for biodiversity preservation

Recent research indicates that a strategy of land conservation can protect more species than land sharing involving less intensive production methods (Phalan et al., 2011). Meyfroidt et al. (2010) used time series to analyze seven tropical countries that have undergone a transition from deforestation to reforestation. Their results showed that the conservation of natural landscapes involved a shift in the trade of agricultural and forestry products towards a larger net displacement, partially offsetting the gains of domestic nature protection through increased use of nature in other countries. In an analysis of factors causing deforestation in 41 tropical countries, Defries et al. (2010) showed that deforestation can be explained in part by urbanization, which is a sign of economic development, and the net export of agricultural products. While our cross-sectional analysis does not capture these dynamics, it still provides important insights into the question of land conservation.

Across our data set, with a doubling of per-capita biocapacity, the actual land use increased by only 70%, indicating that a larger share of land is set aside for nature if there is a lower population density or more productive land. Of the additional land use associated with a doubling of biocapacity, 60% went to export, while only 40% to increased domestic consumption (Table S1). This finding supports the conclusion that export production causes important pressures on land use and thus biodiversity in less populous countries. Our snapshot offers limited insight into a future development with increasing affluence and population and increasing biocapacity due to the intensification of agriculture and forestry. In most regions, population growth has been balanced by increases in agricultural productivity over a 40-year-time period. The total demand for cropland, however, has increased as a result of a shift to more affluent, protein-based diets (Kastner et al., 2012). Moreover, our analysis shows that the demand for forestry products and especially seafood is even more dependent on income, with income elasticities of 0.4 and 0.7, respectively, compared to 0.25 for cropland. If forestry and fish production cannot be intensified to a greater extent than crop production, pressure on biodiversity from these activities will increase faster than from agriculture.

A linear regression (Table S1) indicates that the *net* displacement of land varies most strongly with biocapacity (−0.23 ± 0.05 gha/p net displacement per gha/p biocapacity, normalized regression coefficient of 0.7) but increases with 0.1–0.4 gha/p for each additional $10,000 in income per person (95% confidence interval, normalized regression coefficient of 0.25). This increased net displacement constitutes about one third of the additional land footprint with increasing wealth. Other countries must absorb the land use displacement caused by the current income and population growth in most countries. This paradox suggests that current patterns of net displacement cannot be sustained in the future and must already be changing. Given the key findings that increasing net displacement is associated with the forestry transition (Meyfroidt et al., 2010) and decreased net displacement with deforestation (Defries et al., 2010), a reduced scope for future net displacement limits our ability to protect biodiversity. These negative dynamics could only be changed if either economic growth was decoupled from increasing land footprint requirements or if the land productivity gains in less affluent countries was accelerated such that it surpasses increased requirements due to population and economic growth.

4.3. Future land use

Using individual country population and GDP projections following (Tilman et al., 2011) and adjusted per-capita biocapacity (considering population increase), our regression equation would yield a 70% increase in the global land footprint by 2050 compared to 2004. This does not take into account the potential additional demands on land use for bioenergy and biomaterials given climate mitigation efforts. This extrapolation is based on current global hectares and does not take into account a possible and likely productivity increase. It is, however, a measure and reflection of the increasing pressure on land that can only be met through intensification or expansion. Without productivity increases, the area of unexploited bioproductive land would be reduced from 34% to 6% of global biocapacity. Without considering the increase in population density reflected in the per-capita biocapacity variable, the global land footprint would increase by 85%, which is roughly in line with the doubling of food demand projected by Tilman et al. (2011). Our projected increase of 40% by 2030 provides independent support for the "business as usual" scenario by Wirsenius et al. (2010). Our analysis hence supports the notion that increased biomass demand and the resulting land use present an important sustainability challenge that is caused by a combination of population growth and increasing affluence.

4.4. Sharing responsibility

The translocation of environmental pressures through international trade (e.g., via land use displacement) has only recently received attention and is confounding the issue of responsibility in international policy making. Peters et al. (2011b) demonstrated that countries with emissions reduction obligations (Annex B of the Kyoto Protocol) have displaced an increasing share of their CO_2 emissions to countries without emissions caps. By connecting species threats as recorded in Red Lists to economic activity in a multiregional input–output model, Lenzen et al. (2012) showed that international trade was responsible for 30% of the identified threats to animal species. Species threats connected to international trade occurred primarily in developing countries and were caused by exports of agricultural and forestry products to high-income countries. Our results broadly support these findings (Lenzen et al., 2012) by linking this phenomenon to a plausible mechanism for biodiversity loss (Hertwich, 2012), although multiple variables are acknowledged to play a role in biodiversity decline (Mooney et al., 2005).

The observed pattern of displacement of environmental pressures raises the issue of co-responsibility of high-income countries for losses of biodiversity and ecosystem services in low-income countries. It provides a strong rationale for mechanisms by which high-income countries can contribute to the protection of biodiversity. In the negotiations under the UN Framework Convention on Climate Change (UNFCCC), the issue of responsibility has been translated to a modest funding of both adaptation and mitigation measures in developing countries.

Two important international mechanisms for biodiversity conservation are already being developed: one addresses land conservation through payments for Reducing Emissions through Reduced Deforestation and Forest Degradation in developing countries (REDD+) and similar payments for ecosystem services (Kinzig et al., 2011). The other mechanism is certification schemes for sustainable bioresource use, such as those provided through the Marine Stewardship Council, the Forest Stewardship Council and various biofuels certification initiatives (Butchart et al., 2010; Phalan et al., 2011). While the effectiveness of these mechanisms is still limited, the mutual self-interest of and benefit received by both high-income and low-income countries dictates a systematic extension of these mechanisms.

There is, however, a fundamental question of whether biodiversity conservation efforts through the protection of selected areas or the cessation of particularly high-impact practices can ever be sufficient (Hertwich, 2012). Our research has shown that total per-capita biomass use rises monotonically with income, and even if some areas are set aside or sustainably managed, indirect land use change as identified in the biofuels debate causes an overall increase of the pressure on land (Searchinger et al., 2008). Both intensification and land use expansion tend to impact biodiversity.

4.5. Sharing the planet

For a large fraction of the very poor population, subsistence agriculture and pasturalism constitute the most important sources of food. The poor often hold no formal title to the land on which they live and make their livelihood. Increasing demand for foreign land due to increasing income and population in high and medium income countries puts an increasing pressure on subsistence land use, as evidenced through land grabbing (Cotula et al., 2009), potentially depriving the very poor of their ability to support themselves. Our analysis suggests that this pressure will increase unless the trend of increasing displacement of land use linked to increasing affluence and decreasing per capita biocapacity can be stopped. It is paradoxical that a development that increases the economic value of the productive resource of poor farmers and herders is also a threat to them; the recognition and formalization of traditional land ownership could theoretically alleviate some of these problems.

To reverse the trend of an increasing resource demand by rich countries, Kitzes et al. (2008) suggested the expansion of the "contraction and convergence" framework (Meyer, 2000) used in the global debate on carbon emissions to the wider range of ecological demands humans are placing on the planet. Sustainable intensification (Foley et al., 2011) can certainly meet part of the unmet biomass demand; however, at one point, our land footprints will have to stop growing and, for the sake of biodiversity conservation and the sharing of global resources, may have to decline in some rich countries.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2012.12.010. More information can be found in the online calculator tool http://www.carbonfootprintofnations.com.

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