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Development of consumption-based land use indicators

Synthesis report

For our Environment

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Development of consumption-based land use indicators

Synthesis report

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Kurzbeschreibung

Mit diesem UFOPLAN-Vorhaben zu Landnutzungsindikatoren verfolgte das Umweltbundesamt das Ziel, Indikatoren aus einer Konsumperspektive weiter zu entwickeln, um damit die Deutsche Nachhaltigkeitsstrategie zu unterstützen. Dabei wurden sowohl flächenbasierte als auch wirkungsorientierte Indikatoren mit einbezogen. Ferner hatte das Projekt das Ziel, ausgewählte Indikatoren des Flächenfußabdrucks für Deutschland und die EU zu berechnen. Diese Indikatoren sollen ein verbessertes Verständnis der globalen Zusammenhänge zwischen Konsum und Landnutzung liefern, welches für politische Entscheidungen in Richtung einer nachhaltigen Landnutzung von hoher Bedeutung ist.

Dieser Synthesebericht präsentiert die Schlüsselergebnisse aus diesem Vorhaben. Zuerst geben wir einen strukturierten Überblick über bestehende Berechnungsmethoden des Flächenfußabdrucks, und beschreiben die technischen und strukturellen Eigenschaften sowie ihre Vor- und Nachteile. Dies führt zur Spezifizierung einer hybriden Methode als bevorzugten Berechnungszugang. Im zweiten Teil stellen wir die entwickelte innovative, hybride Methode zur Berechnung des Flächenfußabdrucks vor. Diese besteht einerseits aus einem globalen Handelsmodell, welches Produktflüsse in physischen Einheiten abbildet und es erlaubt, die in den Produkten enthaltenen Landflächen entlang globaler Wertschöpfungsketten zu verfolgen. Andererseits wurde ein Umwelt-Input-Output Modell in komplementärer Form integriert. Diese Methode wurde angewandt, um die Flächenfußabdrücke für Ackerland, Grünland sowie Waldflächen sowohl für Deutschland als auch die EU zu berechnen. Schließlich wurde ein Überblick über bestehende Indikatorensysteme zur Abbildung der Umweltfolgen von Landnutzung gegeben und diskutiert, in wie weit diese flächenbasierte Fußabdruckindikatoren in komplementärer Form ergänzen können. Einige der wirkungsorientierten Indikatoren wurden auch quantifiziert, insbesondere der Entwaldungsfußabdruck. Der Synthesebericht schließt mit einem Überblick über jene Themen ab, die in zukünftigen Arbeiten adressiert werden sollten.

Abstract

With this UFOPLAN project on land use indicators, the German Federal Environment Agency aimed at further developing indicators from a consumption perspective in support of Germany's sustainability strategy, covering both area-based and impact-oriented land footprint indicators. The project also aimed at calculating selected land footprint indicators for Germany and the EU. These indicators should provide an improved understanding of the global teleconnections of consumption and land use relevant for policy making towards achieving sustainable land use.

This synthesis report presents the key results from this project. First, we present a structured overview of existing approaches for estimating land footprints and describe their technical and structural characteristics as well as their strengths and weaknesses. This leads to the specification of a hybrid methodology as the preferred calculation approach. In the second part, we present the developed innovative hybrid land footprint method, consisting of a global land flow accounting and trade model capturing commodity flows in physical units to track embodied land along global supply chains. For non-food commodities the supply chains were complemented by an environmental input-output model. This method was used to calculate the cropland, grassland and forestland footprint of Germany and the EU. Finally, an overview of existing indicator systems for representing the environmental impacts of land use was provided and their complementary usage to extend area-based land footprints was discussed. A few of these complementary indicators were also quantified, most notably the deforestation footprint. The synthesis report closes with an overview of the thematic areas that need to be addressed in future research.

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Acronyms

UBA	Umweltbundesamt (German Federal Environment Agency)
StBA	Statistisches Bundesamt (German Federal Bureau of Statistics)
GHG	Greenhouse gas
EU	European Union
IO	Input–output
Gt	Giga ton = 1 billion tons
ha	Hectare
Mha	Million hectares
ha-eq.	Equivalent hectares (= normalized hectares)

Zusammenfassung

Mit diesem UFOPLAN-Vorhaben zu Landnutzungsindikatoren verfolgte das Umweltbundesamt das Ziel, Indikatoren aus einer Konsumperspektive weiter zu entwickeln, um damit die Deutsche Nachhaltigkeitsstrategie zu unterstützen. Dabei wurden sowohl flächenbasierte als auch wirkungsorientierte Indikatoren mit einbezogen. Ferner hatte das Projekt das Ziel, ausgewählte Indikatoren des Flächenfußabdrucks für Deutschland und die EU zu berechnen. Diese Indikatoren sollen ein verbessertes Verständnis der globalen Zusammenhänge zwischen Konsum und Landnutzung liefern, welches für politische Entscheidungen in Richtung einer nachhaltigen Landnutzung von hoher Bedeutung ist.

Kritische Betrachtung von Methoden zur Berechnung von Flächenfußabdruckindikatoren und Empfehlungen für deren Weiterentwicklung

Robuste Indikatoren zur Beschreibung des Flächenfußabdrucks können eine wertvolle Ergänzung zum derzeitigen konsumbasierten Ressourcennutzungsindikator der deutschen Nachhaltigkeitsstrategie darstellen.

Verschiedene Ansätze und Methoden zur Quantifizierung von konsumbasierten Landnutzungsindikatoren stehen zur Verfügung. Generell kann man zwischen drei Ansätzen unterscheiden: a) *ökonomischen Bilanzierungsansätzen*, die Input-Output-Analyse anwenden, um Ressourcenflüsse entlang von Wertschöpfungsketten zu verfolgen, b) *physischen Bilanzierungsansätzen*, die produktspezifische physische Informationen über die Produktion, die Verwendung und den Handel mit land- und forstwirtschaftlichen Produkten und verarbeiteten Biomasseprodukten verwenden, und c) *hybriden Bilanzierungsansätzen*, welche Elemente beider Methoden miteinander kombinieren.

Die mit verschiedenen Ansätzen ermittelten Flächenfußabdrücke variieren stark, wobei die Unterschiede vorwiegend auf den Umfang und Detailgrad bei der Erfassung von Produkten und Wertschöpfungsketten sowie auf Verzerrungen durch die Verwendung von monetären Flüssen als Annäherung für physische Flüsse zurückzuführen sind. Der Bericht erläutert Optionen und gibt klare Empfehlungen für die Weiterentwicklung von Methoden zur Bilanzierung von tatsächlichen und virtuellen globalen Biomasse- und Landflüssen. Dabei werden insbesondere die Vorteile hybrider Bilanzierungsansätze als ein robuster und transparenter Rahmen für die Berechnung von Flächenfußabdrücken aufgezeigt.

Berechnung des Flächenfußabdrucks Deutschlands und der EU mittels eines hybriden Bilanzierungsmodells

Der Flächenfußabdruck untersucht die Beanspruchung von Landressourcen aus der Sicht des Verbrauchers. Die vorliegende Studie beschreibt eine neue hybride Methode zur Berechnung von Flächenfußabdrücken, basierend auf einem global konsistenten Top-down-Ansatz und der Kombination von physischen und ökonomischen Bilanzierungsansätzen. Der physische Ansatz verfolgt anhand der landwirtschaftlichen Versorgungsbilanzen und bilateralen Handelsdaten der FAO die Wertschöpfungsketten von Nahrungsmitteln vom "Feld zum Teller" und von Nichtnahrungsmitteln vom "Feld zur technischen Nutzung". Die ökologisch-ökonomische Bilanzierung dient dann der weiteren Verfolgung von Non-Food-Rohstoffen bis zum Endverbrauch.

Die hybride Methode wurde angewandt, um jährliche Fußabdrücke zwischen 1995 und 2010 für global 21 Regionen (einschließlich der großen Volkswirtschaften wie USA, China, Indien) zu berechnen. Die Ackerland-Fußabdrücke auf Pro-Kopf-Basis und deren Zusammensetzung variiert weltweit erheblich. Detaillierte Ergebnisse für Deutschland und die EU-28 heben die höhere Landnachfrage von stark auf tierischen Produkten basierten Ernährungsweisen im Vergleich zu pflanzenbasierter Ernährung hervor. Sie zeigen die zunehmende Globalisierung der Märkte und die zunehmende Bedeutung des Non-Food-Sektors für den Flächenfußabdruck im letzten Jahrzehnt.

Der Flächenfußabdruck eines Deutschen belief sich im Jahr 2010 auf rund 2.700 m² Ackerland, etwa die Hälfte davon für tierische Nahrungsmittel, ein Viertel für pflanzliche Nahrungsmittel und ein Viertel für Non-Food-Produkte. Zusätzlich werden für den Konsum von Produkten von Wiederkäuern pro Kopf mehr als 1.600 m² Grünland beansprucht. Deutschland ist ein bedeutender und wachsender Handelspartner mit aktuellen Nettoeinfuhren von 10,6 Millionen Hektar. Insgesamt stammen damit die Hälfte der 22 Millionen Hektar des Ackerland-Fußabdrucks von Anbauflächen im Inland und die andere Hälfte von Landressourcen im Ausland. Auch beim Grünland-Fußabdruck deuten die Ergebnisse trotz bestehender Datenunsicherheiten darauf hin, dass Deutschland ein bedeutender Nettoimporteur ist.

Wirkungsorientierte Erweiterung von Flächenfußabdruckindikatoren zur besseren Charakterisierung von nachhaltiger Landnutzung

Um die Nachhaltigkeit der Landnutzung besser beurteilen zu können, sind um die reine Flächennutzung hinausgehende Analysen nötig, welche die Zusammenhänge zwischen den beanspruchten Flächen und den landnutzungsbedingten Umweltauswirkungen abschätzen. Der vorliegende Bericht behandelt die Erweiterung des Flächenfußabdrucks mit aussagekräftigen wirkungsorientierten Indikatoren zur Erfassung der Auswirkungen verschiedener Konsummuster auf die Ökosysteme und Nachhaltigkeit von Landnutzung.

Der Bericht gibt einen Überblick zu potentiellen Indikatoren und diskutiert folgende als besonders relevant identifizierte Schlüsselindikatoren: Systemindikatoren, welche die flächenbasierten Fußabdrücke mit der global sehr unterschiedlichen potentiellen Flächenproduktivität qualifizieren, den Entwaldungsfußabdruck, den landwirtschaftlichen Energieverbrauch und die landwirtschaftliche Bewässerung im Verhältnis zur lokalen Wasserknappheit.

Eine beispielhafte Berechnung des Entwaldungsfußabdrucks für Nahrungsmittel zeigte etwa, dass dieser Indikator 2005 seinen Höhepunkt erreichte, während er für Non-Food-Produkte weiterhin anstieg und zwischen 2005 und 2010 bereits für 45 % des gesamten Entwaldungsfußabdrucks Deutschlands verantwortlich war.

Weitere Entwicklungsmöglichkeiten

Während bedeutsame Fortschritte in diesem Vorhaben erreicht wurden, bleiben einige Fragen für zukünftige Forschung und Entwicklung offen.

- Nutzung von verfügbaren nationalen Statistiken, um FAO-Daten im Modell in bestimmten Fällen durch offizielle Handels- und Landwirtschaftsstatistiken zu ersetzen und so ein sogenanntes SNAC-Modell (‚single-country national accounts consistent‘) zu erstellen.
- Detailliertere Berichterstattung von Ländern und Produkten durch eine weitere Detaillierung des Fußabdruckmodells und der Nutzung einer transparenten Aufkommens- und Verwendungsstruktur.
- Entwicklung und Analyse weiterer wirkungsorientierter Indikatoren durch die Nutzung detaillierter geografischer Datenbanken und die Anwendung räumlicher Downscaling- und Modellierungsmethoden.
- Fokussierung zukünftiger Analysen auf die Nachhaltigkeit von Schlüsselbereichen des deutschen Flächenfußabdrucks, etwa auf tierische Produkte oder auf den dynamischen und stark auf importierte Rohstoffe angewiesenen Bereich der Nichtnahrungsmittel.

Summary

With this UFOPLAN project on land use indicators, the German Federal Environment Agency aimed at further developing indicators from a consumption perspective in support of Germany's sustainability strategy, covering both area-based and impact-oriented land footprint indicators. The project also aimed at calculating selected land footprint indicators for Germany and the EU. These indicators should provide an improved understanding of the global teleconnections of consumption and land use relevant for policy making towards achieving sustainable land use.

Review of land flow accounting methods and recommendations for further development

Robust land footprint indicators can potentially extend the consumption-based resource use indicator of the German sustainability strategy.

Various approaches exist for quantifying the land embodied in international trade flows and consumption, i.e. the land footprint. These can be classified into a) environmental-economic accounting approaches, applying input-output analysis and tracking supply chains in monetary values, b) physical accounting approaches, using an accounting framework based on data for production, trade and utilization of agricultural and forestry commodities and tracking supply chains in physical units, and c) hybrid accounting, combining elements from both environmental-economic and physical accounting.

The results of recent studies vary widely. Differences are mainly attributable to the product and supply chain coverage and detail, and biases introduced by the use of monetary flows as a proxy for physical flows. The report outlines options and gives clear recommendations for the further development of actual and virtual global biomass and land flow accounting methods, particularly highlighting the advantages of hybrid accounting approaches as a framework for the robust and transparent assessment of land footprints associated with global biomass flows.

Quantifying the land footprint of Germany and the EU using a hybrid accounting model

Footprint analysis reveals the appropriation of land resources from a consumer's perspective. We here present a novel hybrid land-flow accounting method for the calculation of land footprints, employing a globally consistent top-down approach and combining physical with environmental-economic accounting. Physical accounting tracks food products from 'field to plate' and non-food from 'field to industrial use' using the large harmonized FAO data to track biomass flows and related land use in physical volumes. Environmental-economic accounting is used to further track non-food commodities to final consumption.

The hybrid method has been applied annually between 1995 and 2010 for 21 regions globally and including major economies separately (e.g. USA, China, India). Per capita extents and composition of cropland footprints vary widely across the world. Detailed results for Germany and the EU28 highlight the higher land demand of livestock-based diets compared to crop-based diets, the growing integration in international markets, and the growing importance of the non-food sector.

In 2010, the land footprint of each Germany citizen appropriated on average about 2700 m² cropland – about one half for animal source foods, one quarter for crop products, and one quarter for non-food products). Additionally, more than 1600 m² of grassland per capita are used for the consumption of ruminant livestock products. Germany is a major and increasing trading partner with current net cropland imports of 10.6 Million hectares. Overall, half of Germany's 22 Million hectares cropland footprint relies on domestic cultivation and half on land resources abroad. Despite uncertainties in the calculation of grassland footprints, results point towards Germany being a significant net importer.

Extending land footprints towards characterizing sustainability of land use

Beyond area extents, additional information is needed to assess the sustainability of land use, requiring further analyses regarding environmental impacts and preservation of land quality and ecosystem services. This report discusses extensions of area-based land footprints with meaningful impact-oriented indicators for the assessment of the effects of different consumption patterns on the ecosystems and sustainability of land use.

The report gives an overview on potential indicators and discusses the following key indicators, which were identified as particularly relevant during an export workshop: System indicators, which qualify the area-based footprints across globally very different potential land productivities, deforestation footprint, energy use in agriculture, and irrigation water use in agriculture classified by degree of water scarcity.

An exemplary calculation of the deforestation footprint showed that this indicator reached its peak for foodstuffs in 2005, while it continued to grow for non-food products and was responsible for 45 % of Germany's total deforestation footprint between 2005 and 2010.

Options for further development

While significant progress has been made in this project, some questions remain open for future research and development.

- Use of available national statistics to replace FAO data in the model in certain cases through official trade and agricultural statistics, building a so-called SNAC model (‚single-country national accounts consistent').
- More detailed reporting of countries and products by further detailing the footprint model and using a transparent supply and use structure.
- Development and analysis of further impact-oriented indicators through the use of detailed geographic databases and the application of spatial downscaling and modelling methods.
- Focus of future analyses on the sustainability of key areas of the German land footprint, for example on animal products or on the dynamic area of non-food products, which is strongly dependent on imported raw materials.

1 Introduction

The world economy is increasingly globalized with ever more complex supply chains and trade relations. Changes in consumption patterns or the implementation of land use policies in one country may therefore cause displacement or leakage effects and trigger changes in land use and management elsewhere (Bruckner et al., 2015; Yu et al., 2013). For example, a conservation policy aiming at reducing pressures on domestic land and ecosystems may relocate land use and related environmental impacts to other world regions. Equally, a policy, the aim of which is reducing carbon emissions by substituting renewable for fossil resources, may increase the pressure on land systems both domestically and abroad. Consumers and policy makers may not be aware of all direct and indirect environmental and social impacts of policy measures and consumption activities. Thus, the sustainability of the global land system depends both on the consumer demand and preferences as well as the scale and management practices applied for the production of primary commodities, and their interlinkages.

Trends and patterns of global biomass consumption and land use are key determinants for global sustainable development. This is particularly true for agriculture, which is facing multiple challenges threatening global food supplies, including an increasing world population, changing diets, increasing demand for bioenergy and bio-materials and climate change impacts. Furthermore, increasing global demand for food, feed and bioenergy may cause land clearing of up to 1 billion hectares by 2050 (Tilman et al., 2011). This area corresponds to two thirds of the cropland currently under use. Such massive land use changes would result in annual GHG emissions of about 3 Gt of carbon, equivalent to 20 % of all current anthropogenic GHG emissions.

Over the recent years, production and consumption of biomass and related implications for land use have also developed into important issues in environmental and resource policy strategies on the European level. For example, in the EU Resource Efficiency Roadmap (European Commission, 2011), land is one of four core resource categories that should be monitored with high-level macro-indicators. The Commission has explicitly addressed the need to further develop indicators illustrating indirect land embodied in products (European Commission, 2012a). The EU Bioeconomy Strategy (European Commission, 2012b) has set bio-based products and related impacts on land and ecosystems in the centre of the initiative.

The threat of a possible expansion of agricultural land is endangering some of the most precious ecosystems, particularly outside Europe. In this context it becomes increasingly important to measure and monitor global land use implications of consumption patterns and associated policies. Area-based land footprint indicators and their impact-oriented extensions intend to characterize the land-based commodity supply systems and their related land use intensities and changes from a consumer perspective. The aim is to relate prevailing national consumption patterns with observed global land use and to attribute associated resource uses and environmental impacts to final consumption.

Against this background, the German Federal Environment Agency (Umweltbundesamt, UBA) commissioned a research project in support of UBA and the German Federal Bureau of Statistics (Statistisches Bundesamt, StBA) to further develop and establish land footprint indicators for monitoring global implications of German and EU consumption on land use and related environmental impacts. The aim of this project was to further develop indicators from a consumption perspective in support of Germany's sustainability strategy, covering both area-based and impact-oriented land footprint indicators. Further, the project aimed at calculating selected land footprint indicators for Germany and the EU. These indicators should provide an improved understanding of the interlinkages of consumption and land use globally relevant for national and international policy making towards achieving sustainable land use.

Results of the project are presented in three reports. Report 1 aims at providing a structured overview of existing approaches for estimating land footprints describing their technical and structural characteristics, comparing strengths and weaknesses and drawing conclusions on their applicability to measure a country's land demand in third countries (Bruckner et al., 2017). Building on these results, Report 2 presents the innovative land footprint method developed in this project, which consists of a global trade model in physical units to trace embodied land along supply chains complemented with an economic input-output model (Fischer et al., 2017a). Report 2 also includes the results for the land footprints of Germany and the EU. Finally, Report 3 provides an overview of existing indicator systems for representing the environmental impacts of land use and discussed their linkages to and their complementary usage to extend area-based land footprints. A few of these complementary indicators were also quantified, most notably the deforestation footprint (Fischer et al., 2017b).

This synthesis report (Report 4 of the project) summarises and discusses key results from all project tasks. Chapter 2 presents the innovative calculation method for land footprint indicators developed in this project. A set of area-based land footprint indicators for Germany is presented and discussed in Chapter 3. Chapter 4 is devoted to the extensions of area-based with impact-oriented indicators, presenting the deforestation footprint as an example. The concluding Chapter 5 puts the achievements of this project in perspective to the overall research on land footprints and provides recommendations for further developments.

2 Method

2.1 Evaluation of existing land footprint methods

Report 1 (Bruckner et al., 2017) performs a review of existing accounting methods covering around 50 publications in the thematic area of virtual land flows and teleconnections between production and consumption. In addition, selected highly influential papers and reports presenting recent developments in material flow accounting are also considered in the review. In order to perform the comparative evaluation of the various approaches to assess global land flows embodied in final consumption, a list of criteria was set up in cooperation with the Federal Environment Agency and the German Statistical Office. The criteria were grouped into two thematic areas, covering general methodological aspects such as the level of country and product detail and the considered land use types on the one hand, and specific technical aspects such as data sources, data generation and compilation and applied assumptions on the other hand.

The review reveals that three main methodological approaches exist in the literature. (1) '*Environmental-economic accounting*' approaches, where supply chain flows (and embodied land use) are tracked in terms of monetary values. (2) '*Biophysical accounting*' approaches, which are based on physical data for production, trade and utilization of agricultural and forestry commodities, thus tracking supply chains in physical units. (3) '*Hybrid accounting*' approaches, which use a combination of elements from both environmental-economic and biophysical accounting in order to overcome specific limitations or weaknesses of the individual methods (1) and (2).

Environmental-economic accounting, represented by multi-regional input-output (MRIO) analysis, stands out with its comprehensive coverage of the full (global) economy, thus all indirect effects are covered, independently of the complexity of supply chains. IO models avoid truncation errors, as per definition all products, including highly-processed biomass-based products are being considered by the calculations. Major disadvantages include the limited commodity detail determined by the sector definitions of the IO model as well as problems related to the allocation of land flows following monetary supply chain structures.

A major advantage of biophysical accounting is the high level of commodity detail, which allows a more consistent allocation of land to harvested biomass. Biophysical accounting approaches are also superior regarding the geographical coverage and detail, the level of detail on products and land use types and timeliness of the calculations. However, data availability clearly restricts the applicability of this second approach. This refers particularly to the limited availability of data for higher processed products, which lead to a partly incomplete representation of certain supply chains as well as to the use of product-specific land intensity coefficients, which often stem from a large variety of sources with potentially weak consistency and representativeness.

Hybrid approaches have the potential to exploit the specific advantages of the biophysical and environmental-economic accounting methods and can thereby overcome some of the underlying limitations and weaknesses.

Report 1 concludes that, overall, biophysical accounting methods are in a better position for providing a solid basis for further developments due to their high level of commodity detail, their potential to apply a physical allocation scheme for tracking land flows along global supply chains and their ability to distinguish between different categories of designated end use such as food use, feed use and non-food use (e.g. for textiles or bioenergy). The report also highlights that top-down applications of the biophysical accounting approach can be extended with monetary MRIO models to form a hybrid accounting method, in order to comprehensively capture all global biomass flows from harvest to final consumption. This could lead to a consistent top-down accounting model combining biophysical and monetary values in a fully integrated hybrid or mixed-unit input-output model.

2.2 The hybrid land footprint method developed in this project

Following the recommendations of Report 1, this project developed a hybrid accounting approach, combining elements from environmental-economic and biophysical accounting, in order to set up a globally consistent top-down accounting framework comprising all supply and value chains of bio-based products.

This innovative method is the first to combine a state-of-the-art global physical accounting and trade model, i.e. IIASA's LANDFLOW model (IIASA et al., 2006; Prieler et al., 2013), with the latest available monetary MRIO models for detailed environmental assessments. The hybrid model developed in this project applies time series from 1995 to 2010 from the highly detailed FAOSTAT database and the MRIO tables from EXIOBASE v3 (Tukker et al., 2013; Wood et al., 2015).

This global hybrid method allows tracking embodied land on a high product and country detail for raw materials and products with a low level of processing based on supply chain data in physical units. The method thus enables considering differences with regard to applied technologies and countries of origin for each biomass-based product. In order to overcome current limitations of physical accounting approaches in tracking processed commodities and finished goods with more complex production chains, in particular regarding non-food bio-products (crop-based such as textiles or bio-based energy carriers and animal-base such as leather), the physical model is connected to an environmental-economic accounting method (i.e. the MRIO model). This allows considering the full upstream resource requirements and thus illustrating all indirect effects of final consumption, independently from the complexity of supply chains.

Compared to other existing land footprint methods, this new method is characterised by a number of key advantages.

- The method applies a top-down approach with global coverage and thus avoids applying the domestic technology assumption, i.e. the assumption that imported products are produced using the same input structure compared to domestically produced goods. Thereby, global consistency of land attribution along supply chains can be fully maintained.

- The method uses reported global cropland and grassland statistics, captures multi-cropping and fallow practices and applies forest yield data and model estimates for forest areas.
- It avoids errors resulting from inconsistencies between monetary national accounts and land use statistics by using a biophysical accounting method for raw materials and products with a low level of processing. At the same time, it ensures full coverage of all bio-based commodities and supply chains, including highly processed non-food commodities, by extending the physical with a monetary MRIO model.
- Finally, the method contains a consistent and balanced representation of bilateral trade flows, fully considering re-exports and transit trade.

The developed method is therefore very well suited to perform comparative assessments of land footprints across a large number of countries worldwide. The high level of regional coverage, achieved through the application of global physical and economic data sets, however, also points to a potential disadvantage of the developed method. The applied international statistics provided by the various organisations of the United Nations may differ from national statistics or provide less detail than national sources. For example, the developed model applies the volume weighted land content of domestic production and imports for a specific commodity to the exports. In case of major differences between the land contents of imports and domestic production (e.g. soybeans produced in Germany with higher yields compared to imported soybeans from South America), this may lead to some inaccuracy in the land contents of exports. Achieving a very high level of international coverage and harmonisation therefore comes at the price of disregarding national information. As the analysis in Report 2 (Fischer et al., 2017a) revealed, the results from the method developed in this project differ from the results obtained with the land footprint method from the German Statistical Office (Mayer et al., 2014), notably due to differences in the employed land use data.

These encountered problems could be avoided by constructing a single-country national accounts consistent (SNAC) model (compare with Edens et al., 2015) based on the developed trade model by replacing data from international sources for a specific country of interest with data from official national trade and agricultural statistics in cases where national data are considered more reliable or where they can add additional details.

Moreover, the applied model could be enhanced by adding more regional and commodity detail. The currently applied methodology quite substantially aggregates available data to a list of 21 regions and 23 commodities, while FAOSTAT provides data for up to 175 countries and more than 100 commodities. Further improvements could be achieved by availability of more detailed reporting of livestock related data. In particular reliable estimates of extents of grassland actually used for grazing livestock could greatly improve the estimation of grassland footprints.

A more detailed physical allocation model could, in addition, be implemented applying a highly transparent supply and use structure, analogous to that used in the System of Economic and Environmental Accounts. A resulting physical biomass MRIO table can then be combined with a monetary MRIO table, thus realising a consistent and transparent hybrid (or mixed-unit) IO model with global coverage and high detail. In addition to adding detail and transparency, this would also allow the application of analytical tools such as structural decomposition and path analysis in order to further investigate supply chains and developments over time.

3 Area-based indicators

3.1 General reflections

Area-based land footprint indicators can play an important role in the design and monitoring of land-related policies. Core questions that area-based indicators can address include:

- Which land areas are required to satisfy the domestic consumption of products and services and how have these areas developed over time as a consequence of e.g. changes in diets or changes in energy systems?
- Which commodities and consumption patterns contribute most to a nation's land footprint and which priority areas for reducing the land footprint and related environmental impacts can be identified?
- What is the share of the land footprint embodied in imports and how have globalization processes impacted on the global distribution of land resources? What do increased amounts of embodied land imply for policy areas such as trade or development policies?
- What is the land use dimension of the energy or material uses of biomass, particularly in light of the efforts put into the development of the bioeconomy?

In order to address these and other questions, area-based indicators should be developed and applied as a flexible system of information, providing insights at different levels of detail. The communication of the overall land footprint of a country, such as Germany, as a single number might be tempting, in order to transport a simple message to policy makers and the public. However, the aggregated visualization of an indicator that is composed of a number of different components with very different environmental and socio-economic implications can potentially lead to misinterpretations of the result. It is therefore suggested to present area-based indicators in a disaggregated manner and thereby to exploit the full informative potential of the very rich database underlying these indicators. Disaggregation can be undertaken in various dimensions, for example

- Categories of land use, e.g. cropland, grassland or forests
- Product categories, such as vegetables, alcoholic beverages, meat products, biofuels or textiles
- Categories of final use, e.g. food, feed or industrial (non-food) use of biomass
- Origin of biomass and related land areas, in order to separate domestic from foreign land and identify priority areas with potentially high negative environmental impacts, e.g. tropical regions

The various options for disaggregation allow connecting results from land footprint assessments to particular policy-relevant topics, such as the environmental impacts of food consumption or the land use-related consequences of a transition towards bio-energy and bio-based materials. In the project, the aim was therefore to present the results on different levels of disaggregation (see also the following sections).

As the main categories of land, i.e. cropland, grassland and forests, have very different characteristics and face different sustainability challenges, it is suggested to present key indicators for each of the three categories:

- We suggest applying an unweighted, areas-based land footprint indicator as the headline indicator for the category of cropland (see section 3.2).
- As productivities of grassland differ widely between different world regions, an unweighted, area-based land footprint for this second land use category would deliver results, which are difficult to compare and interpret across countries. We therefore suggest applying a productivity-weighted grassland footprint (see section 3.3).
- Similarly, also forest areas are used with widely varying intensity. Moreover, no reliable statistics on global forest land use are available. It is therefore necessary to estimate the use of

forest area in relation to the reported quantities of wood production. We suggest using regional rates of net annual wood increment for that (see section 3.4).

3.2 Cropland footprint

The cropland footprint is an indicator that illustrates the extent of cropland used for the production of goods consumed by a country's population. Three major use categories dominate the cropland footprint:

i) Food use of crops including, for example, cereals, sugar crops, oil crops, vegetables, fruit and spices

ii) Feed use of crops for the production of livestock products comprising, for example, meat and dairy products, eggs and animal fats

iii) Non-food use of crops, for example, vegetable oils for biofuels, cotton for textiles, or animal skins for leather products

In the applied definition, cropland comprises not only temporary but also permanent crops such as coffee and cocoa. The cropland footprint includes both commodities from crops cultivated domestically and abroad. It is therefore calculated as the sum of domestically cultivated areas ('production') and areas embodied in imported products ('imports') deducting the areas embodied in exported commodities ('exports').

Using the hybrid land footprint model as described in Section 2.2 above, cropland footprints were calculated for the period 1995 to 2010 for Germany as well as 20 other major countries and world regions, including the EU-28.

3.2.1 The cropland footprint of Germany

3.2.1.1 Overall composition of the cropland footprint

In 2010, Germany's demand for agricultural commodities required for food and non-food uses and exports was based on crops produced from around 36 million hectares of cropland (Table 1).

Of this land area, around one third is produced domestically and two thirds are sourced from outside Germany and 'embodied' in imported crops and livestock products. At the same time Germany's industry exports and re-exports crops and livestock commodities equivalent to around 13.6 million hectares. In total, Germany is a net importer of virtual cropland.

Germany's cropland footprint in 2010 equalled 22.4 million hectares. Germany's cropland self reliance ratio (cropland in domestic production divided by the cropland footprint) therefore was 53 %. This means that almost half of the cropland required to meet domestic consumption was located outside Germany.

Table 1. Cropland embodied in production, trade and consumption, 2010

Item	Area in 1000 hectares
Domestic crop production	12,088
+ Imports	24,227
Total input into German economy	***36,315***
- Exports	- 13,621
- Stock change	- 336
Cropland footprint	***22,359***

Figure 1 illustrates the composition of Germany's cropland footprint by main use category in the year 2010. Almost half of Germany's cropland footprint (48.5 %) was related to food consumption of livestock products (meat, dairy products, eggs), about one quarter to crop-based food products and another quarter to non-food commodities. Animal-based products therefore contribute to a much larger extent to the overall cropland footprint of Germany compared to crops directly eaten as a vegetarian part of diets.

Figure 1. Composition of Germany's cropland footprint, 2010

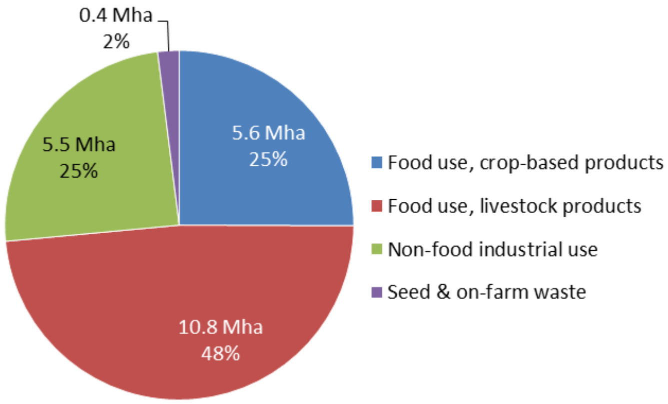


Table 2 provides insights into the development of the cropland footprint of Germany over the years from 1995 to 2010. The share of non-food products increased steadily during the observed 15 years, from 19 % in 1995 to more than 24 % in 2010, while the footprint of crop-based food products decreased by about the same size.

Table 2. Cropland footprint of Germany, 1995 to 2010, in 1000 hectares

	1995	2000	2005	2010
Food use, crop products	6,532	5,853	5,597	5,604
Food use, livestock products	11,315	9,929	10,769	10,835
Other use (non-food)	4,327	4,453	4,796	5,476
Seed & on-farm waste	462	439	403	444
Total	**22,636**	**20,674**	**21,565**	**22,359**

3.2.1.2 The role of international trade

As Table 1 already illustrated, trade plays a major role in determining Germany's overall cropland footprint. Table 3 takes a closer look at the composition of Germany's imports and exports of embodied land by major commodity groups.

Table 3. Cropland embodied in imports and exports, by major commodity group, 2010, in 1000 hectares

	Imports	Exports
Cereals	3,351	1,683
Oil crops	3,287	163
Vegetable oil	3,453	1,925
Oil cakes	1,330	682

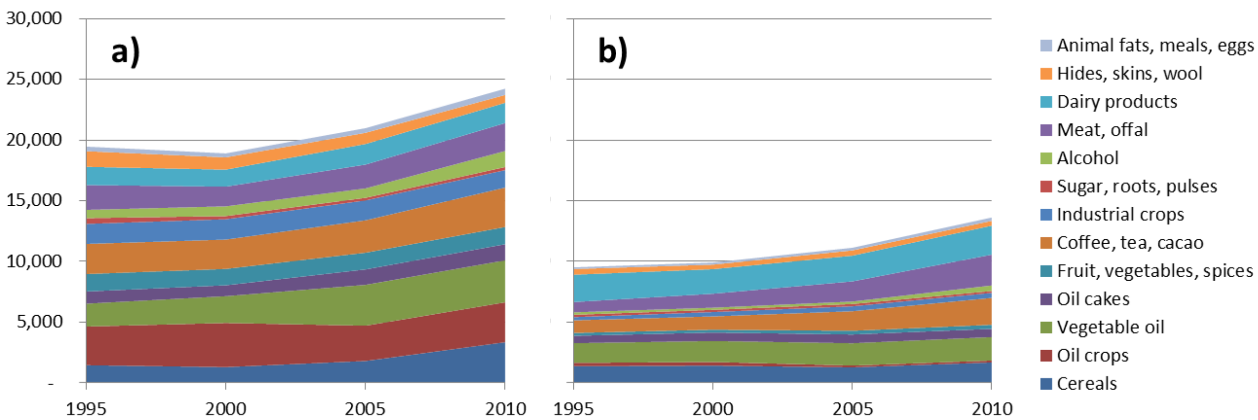
	Imports	Exports
Fruit, vegetables, spices	1,417	333
Coffee, tea, cacao	3,246	2,213
Industrial crops	1,439	417
Sugar, roots, pulses	256	154
Alcohol	1,320	453
Meat, offal	2,295	2,537
Dairy products	1,671	2,389
Hides, skins, wool	647	396
Animal fats, meals, eggs	515	277

One third (33 %, 8 Mha) of this virtually imported cropland was associated with the oil crop sector, including e.g. soybeans, rape seed and palm oil. Other important commodities with large virtually imported cropland included stimulants (coffee, tea, cacao) and cereals, both associated with imported cropland of over 3 Mha, followed by meat (2.3 Mha), dairy products (1.7 Mha) and industrial crops (1.4 Mha).

At the same time, Germany was also an important exporter of food and non-food products and in 2010 (re-)exported almost 40 % (or 14.5 Mha) of total supply (cropland embodied in domestic production and imports of crops and livestock products). Important export commodities were meat products (2.5 Mha), dairy products (2.4 Mha), stimulants (2.2 Mha), and products from vegetable oils (1.9 Mha) and cereals (1.7 Mha), making up almost 80 % of exported commodities.

While cropland cultivated in Germany has hardly changed since 1995, neither in terms of extent nor in terms of crop composition, volumes of commodities and associated cropland areas entering trade increased substantially. Compared to 1995 cropland embodied in imports and exports of crop and livestock products increased by 25 % (+4.8 Mha) and 43 % (+4.1 Mha) respectively (Figures 2a and 2b).

Figure 2. Cropland embodied in Germany's imports (a) and exports (b), 1995 to 2010, in 1000 hectares



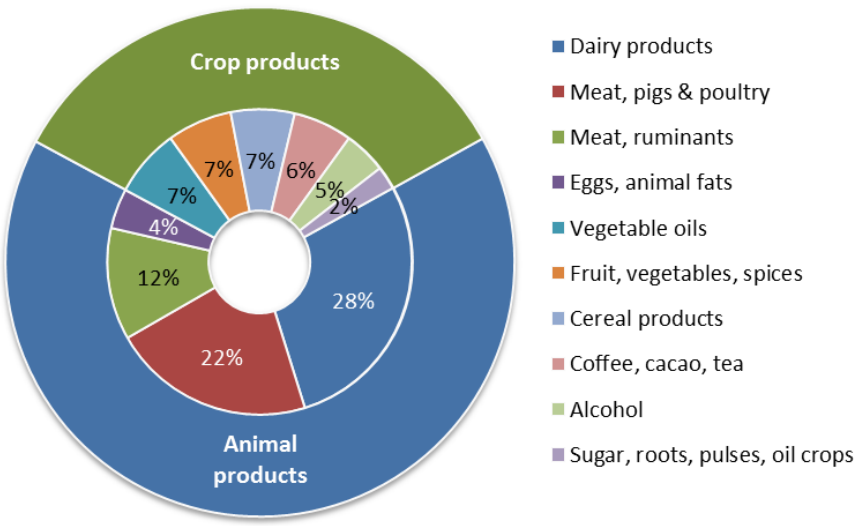
Compared to 1995, cropland embodied in imports increased particularly in the categories of cereals, vegetable oils and cattle meat products. Regarding cropland embodied in exports, the most dynamically expanding product groups were coffee, cacao, tea, as well as animal products from pigs and poultry farming.

Overall, Germany was a significant net importer of cropland across the whole time period with net imports amounting to 10.6 Mha in 2010. However, for the categories of meat and dairy products, Germany was a net exporter of embodied land. This illustrates the position of Germany in the global agricultural trade system, which allows Germany to generate value added by importing unprocessed crops and using these imports in the production of higher value processed livestock commodities, which are exported to other countries. Significant amounts of oilseed cakes, maize and other cereals are produced on cropland outside Germany and used as animal feed to raise Germany's livestock herds. Similarly, Germany's virtual land imports associated with stimulants (coffee, cacao, tea) is three times its domestic use. This means that two-thirds of imports (measured in the respective cultivation areas) are re-exported as higher value goods after processing.

3.2.1.3 The cropland footprint for food consumption

Germany's cropland footprint of food consumption amounted to around 16.4 Mha in 2010. This equalled almost 2,000 m² per capita. Two thirds of this area or around 10.8 Mha were related with the consumption of livestock products (Figure 3).

Figure 3. Composition of cropland footprint for food consumption, Germany, 2010



Main components include dairy products (4.6 Mha), pig and poultry meat (3.5 Mha) and rumiant meat (2.0 Mha). Note that commodities from ruminant livestock (cattle, sheep, goat) require feed on grassland in addition to cropland and thus enlarge the resprective footprint (see section 3.3 below).

A much smaller amount, about one-third of the land footprint of food consumption (5.6 Mha), was associated with products of vegetable origin. About 1.1 Mha was appropriated by the consumption of each of the following commodity groups: i) cereal products; ii) vegetable oils; iii) fruit, vegetables, spices; and iv) stimulants (coffee, cacao, tea).

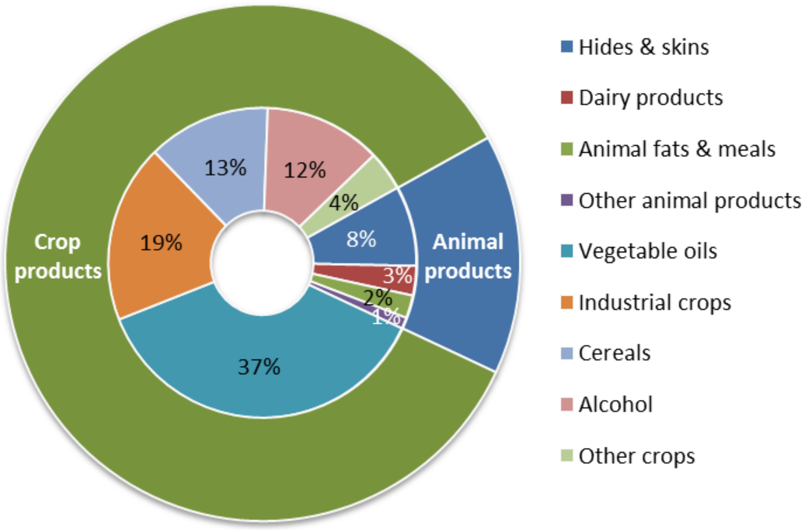
Cropland embodied in Germany's food consumption was in majority (61 %) located within Germany. Some 23 % stemmed from other EU-28 countries. The remaining 16 % originated from non-EU countries, notably in South America (stimulants, fruit), Sub-Saharan Africa (stimulants), and Southeast Asia (stimulants, vegetable oils).

3.2.1.4 The cropland footprint for non-food products

Some 5.5 Mha or 24.5 % of Germany's cropland footprint in 2010 were associated with agricultural commodities used for non-food purposes, for example in the form of fuels, textiles, plastics or pharmaceuticals (henceforth termed 'non-food footprint'). Almost one fifth of Germany's non-food cropland footprint related to industrial crops, including natural rubber, fiber crops, and tobacco, which are cultivated for non-food purposes only.

In return, four fifths of the non-food cropland footprint either compete directly with the food sector (e.g. cereals, dairy products) or they involve co-products (e.g. hides & skins produced together with meat; biodiesel produced together with livestock feed). Vegetable oils are associated with 37 % of the country's non-food cropland footprint, as Figure 4 reveals. These are for example used in the form of agrofuels added to fossil fuels as foreseen by the EU biofuel directive. Ethanol from sugar crops and cereals, as well as bioplastics are some other non-food uses of increasing importance.

Figure 4. Composition of non-food cropland footprint of Germany, 2010



While with 61 % the vast majority of cropland embodied in Germany's food consumption stemmed from the country itself and another 23 % was sourced from other EU countries, for the case of non-food products only 14 % of Germany's cropland footprint was based on domestic land resources or produced on land in the rest of the EU-28, respectively. The remaining 71.4 % of cropland was imported from outside the EU-28. 26 % or 1.4 Mha stemmed from the region of Rest of Asia, including countries such as Indonesia, Malaysia, Bangladesh, Philippines and Thailand. North America, particularly the US, supplied 12 % of Germany's non-food cropland footprint in 2010, mainly in the form of maize (or ethanol derived from maize).

The four most important non-food products were vegetable oils, non-food alcohol, fibres and fibre crops, and maize and derived products. More than 56 % of vegetable oils were imported from outside the EU-28. For non-food alcohol, fibre crops and maize, extra-EU imports account for 84 %, 96 % and 97 % of Germany's footprint, respectively.

Compared to the situation of food products, these results reveal a considerably higher import dependency for non-food products. Increasing demand of Germany in the non-food areas, in particular regarding vegetable oils and ethanol used for substituting fossil fuels, therefore have an overproportional impact in other countries supplying these crops. These results thus support claims to carefully assess the land use changes and related impacts from increasing production of biofuels (see UNEP, 2009).

3.2.2 Comparisons of the cropland footprint

3.2.2.1 European countries in their global context

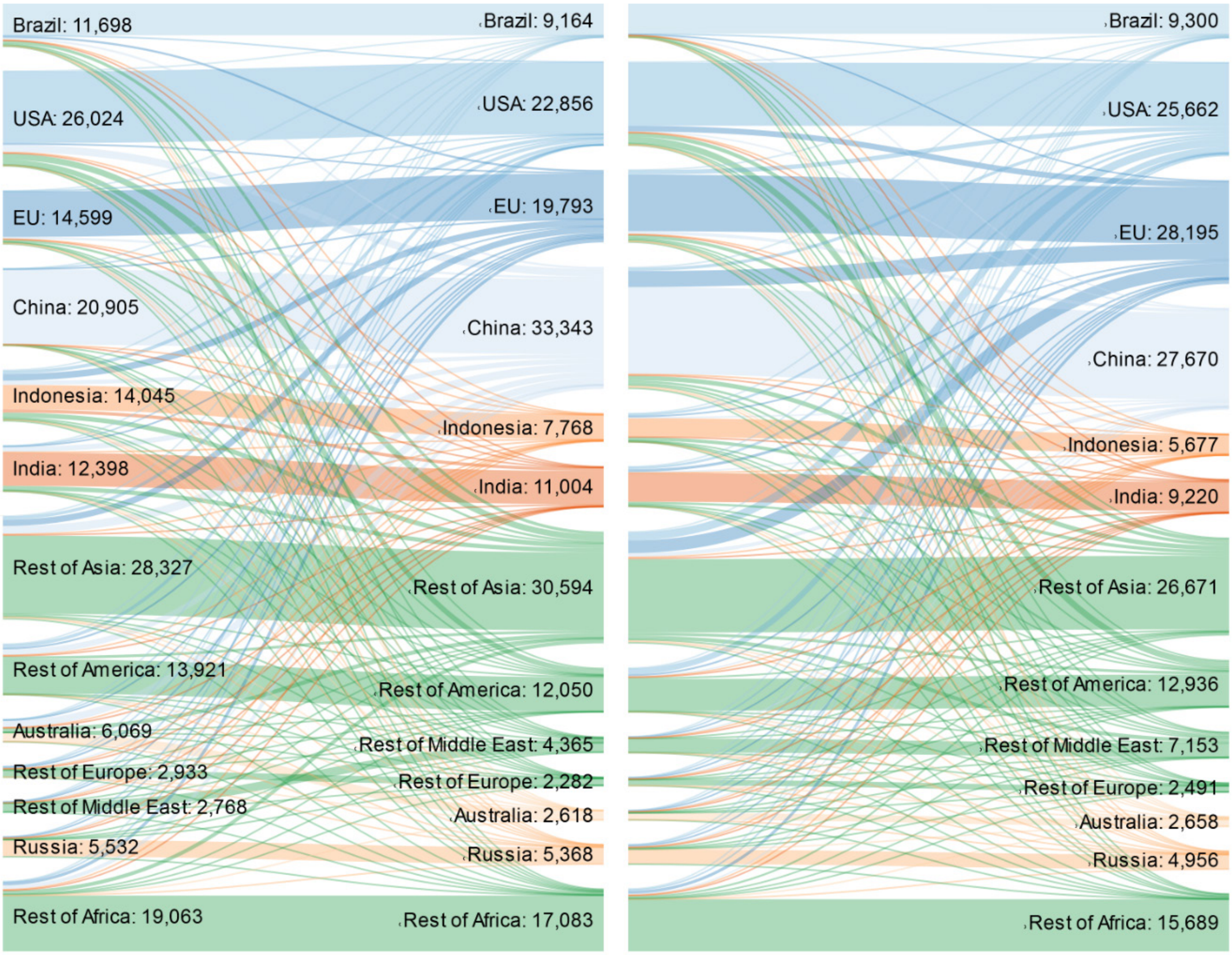
Comparing the German cropland footprint patterns and trends with the ones observed for the European Union reveals several parallels. Cropland available in the countries of the European Union has been continuously decreasing during the last decades, from 131 Mha in 1995 to 121 Mha in 2010. At the same time, overall trade volumes and embodied cropland resources increased. However, net imports of cropland to the EU remained fairly constant over time, amounting to between 35 and 39 Mha. The decrease of the EU cropland footprint from 170 Mha in 1995 to 157 Mha in 2010, thus, came at the expense of domestic cropland use which was reduced significantly.

The composition of the cropland footprint serving food consumption in the EU is very similar to the case of Germany. Almost 60 % of the footprint is associated with animal-based products, such as meat from pigs, poultry and cattle as well as dairy products.

The most notable trend in the composition of the cropland footprint over time was a decreasing proportion of cropland embodied in food products in favour of a higher proportion of non-food uses, which contributed 18 % to the total EU cropland footprint in 2010. The increase in the non-food footprint is to a large extent due to vegetable oils and maize for the production of biodiesel and ethanol.

As the hybrid land footprint model allows disaggregating a large number of producing regions, the origin of the cultivation areas used for non-food purposes can be analysed in detail. Figure 5 shows a flow diagram of non-food products measured in terms of the required cropland areas in the year 2010. On the left side, the crop producing countries and regions are illustrated; the middle part of the diagram refers to the place of industrial processing; while the right side shows the consuming countries and regions.

Figure 5. Cropland flows embodied in non-food products from producing to processing to consuming countries and regions, in 1000 hectares, 2010

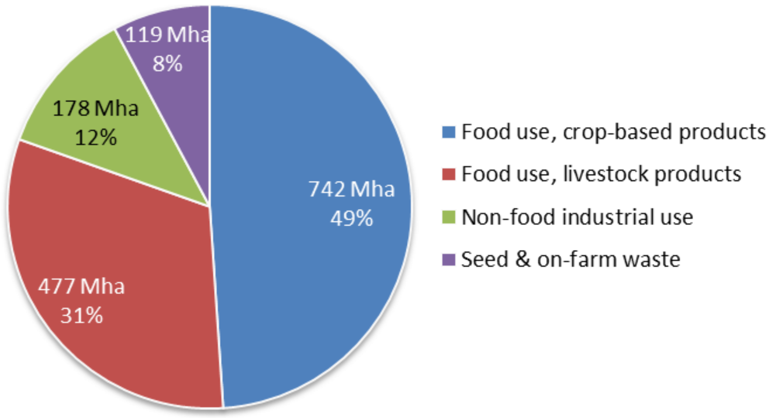


With more than 28 million hectares in 2010, the EU was the largest consuming region of cropland embodied in non-food products, followed by China, Rest of Asia and the USA. Less than half of the land required to produce the non-food products consumed in the EU (around 12.5 Mha) was located in the EU itself. Large amounts of cropland (7.3 Mha) were imported to serve the industrial processing of crops for non-food purposes in the EU, most notably vegetable oils for the oleochemical industry (e.g. soaps, detergents, biofuels, cosmetics) from Indonesia and other Asian countries. Most of the processing output (equalling 19.8 Mha of cropland) served consumption within the EU itself. In addition, processed products were imported from all over the world, in particular from China (4.4 Mha; primarily re-exported vegetable oils), Rest of Asia (3 Mha; vegetable oils and rubber) and the USA (1.6 Mha; mainly maize).

3.2.2.2 Global comparisons

In contrast to Germany and the EU, the composition of the global cropland footprint shows a significantly larger share of food products (Figure 6).

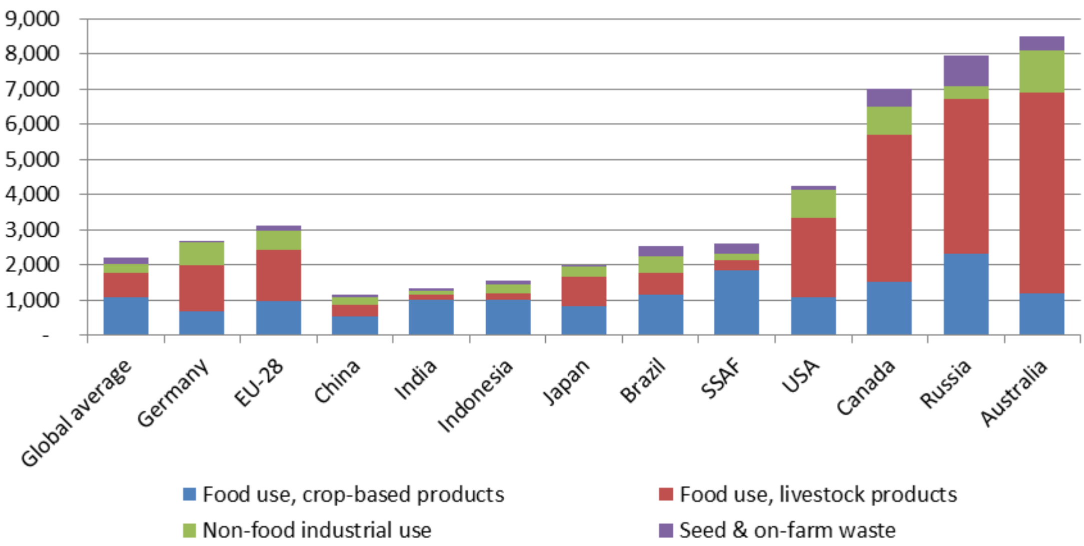
Figure 6. Composition of the global cropland footprint, 2010



In a global perspective, almost half of the cropland footprint was made up by the category of crops cultivated for food purpose, while the share of livestock products was only 31 % in 2010, as opposed to 48 % for the case of Germany. This illustrates the fact that diets in industrialised countries are to a much larger extent based on meat and other animal products, whereas vegetarian or low-meat diets are more commonly found in the Global South. This also implies that diet changes currently ongoing in many developing countries (Kastner et al., 2012) will have a major impact on global land demand. Land used to produce non-food industrial products accounts for only 12 %, compared to 25 % in Germany and 18 % in the EU. On the global level, in particular biofuels, but also other commodities such as textiles, are thus consumed in significantly smaller amounts compared to consumption in industrialised countries.

This difference is further elucidated by Figure 7, which illustrates the cropland footprints of various countries and world regions expressed in square meters per capita, disaggregating the main categories of use.

Figure 7. Composition of cropland footprint of different countries and world regions, in square metres per capita, 2010



Note: SSAF = Sub-Saharan Africa

Figure 7 highlights the distinct regional heterogeneity in scale and composition of cropland footprints of different countries. In 2010, the per capita cropland footprint of the European Union and of

Germany surpassed the world average of around 2200 m^2 by 42 % and 23 % respectively. At the global level, half of the cropland was used for crop-based food products, while in the EU and Germany these accounted for only 31 % and 25 % respectively.

The lowest per capita cropland footprints occurred in densely populated Asian countries including China (around 1100 m^2), India (1350 m^2) and Indonesia (around 1600 m^2). Despite of their restricted per capita cropland resources, India and Indonesia were net exporters of cropland with self-sufficiency ratios of 104 % and 120 % respectively. Due to increasing consumption of animal products, China turned into a net importer of cropland resources with a self-sufficiency ratio of only 78 % in 2010.

The largest cropland footprints (over 7000 m^2 per capita) were found in Australia, Russia and Canada, whereof Australia and Canada both were net exporting regions at the same time. The large footprints in these countries result from extensive cropland management applying fallow periods on relatively large extents of cropland (Australia, 46 Mha; Canada, 48 Mha; Russia, 122 Mha) while at the same time population densities are comparatively low. Sub-Saharan Africa shows the second largest value for crop-based food products, which can be attributed to comparatively low yields.

3.3 Productivity-weighted grassland footprint

The pilot calculations undertaken in this project to compile a productivity-weighted grassland footprint illustrate that for this land use category, which is characterised by highly varying yields per hectare, the weighted perspective reveals different messages as compared to the perspective of actual grassland areas. The self-sufficiency ratio of German consumption of products from grassland increases dramatically, from 34 % to 62 %, when applying a normalization. This change is driven by the fact that some product groups of high importance for Germany's consumption, notably meat and dairy products, are produced on grassland areas, both within Germany and abroad, which have a bio-productivity significantly above global average.

3.3.1 Methodological concept

The bio-productivity of grasslands varies widely across world regions, ranging from highly productive grasslands in South America or Central Europe to marginal lands in semi-arid regions in Central Asia or the northern parts of the Sahel. Calculating an unweighted area-based indicator for the grassland footprint would thus lead to highly diverging results, which would be difficult to interpret and hardly comparable. As a large fraction of global human land appropriation is occurring on grassland areas, this underlines the need for developing meaningful land footprint indicators for this important part of agricultural land use.

Here we propose to normalize grassland footprints relative to the potential biomass productivity at the respective production location. For this purpose, spatially detailed grassland productivity data (for example, from the GAEZ model, IIASA and FAO, 2012) are required for the estimation of average national grassland yields, which are then normalized to defined reference yields. The latter can, for example, be based on the global average grassland yield, or on any defined reference grassland productivity (see below).

The productivity-weighted grassland footprint of a country will therefore be larger than its (unweighted) footprint when animal products are sourced from countries with higher productivity compared to the reference value. Vice versa, when a country consumes significant amounts of commodities from areas where grassland productivity is low, the weighting of the land footprint by potential productivity will decrease a nation's footprint relative to other countries.

For example, applying a reference grassland productivity of five tons per hectare (this corresponds roughly to the average for Central Europe), the reported 3400 million hectares of globally utilized grassland will be diminished to an equivalent of 1400 million hectares reference grassland.

In this project, grassland areas were normalized to a defined reference value of 2.06 tons dry matter yield per hectare. This reference point was selected as it represents mean biomass yield of global grassland areas. Table 4 illustrates the impacts of the normalization procedure on the respective grassland areas for selected countries (IIASA and FAO, 2012).

Table 4. Average grassland yields, reported grassland areas and normalized grassland areas for selected countries, year 2000

	Grassland yield[1] [tons/ha]	Reported grassland[2] [Mha]	Share in global grazing area	Normalized grassland[3] [Mha equivalent]	Share in global norm. grazing area
Germany	6.5	5	0.1 %	16	0.5 %
France	6	10	0.3 %	29	0.9 %
Brazil	5	196	5.8 %	476	14.0 %
Argentina	3	100	2.9 %	146	4.3 %
United States	3	236	6.9 %	345	10.1 %
China	1	400	11.8 %	194	5.7 %
Australia	1	408	12.0 %	199	5.8 %
WORLD	**2**	**3,400**	**100.0 %**	**3,400**	**100.0 %**

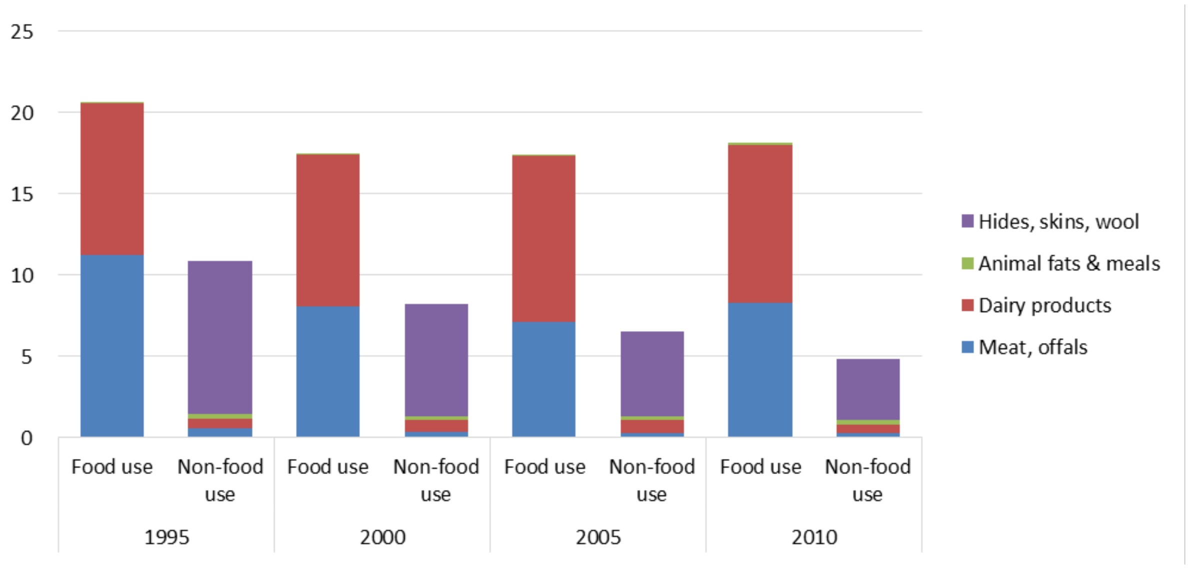
1 Source: GAEZ average over all grid-cells with grassland land use; **2** Source: FAOSTAT; **3** Normalized to 2.06 tons/hectare, i.e. normalized grassland area = reported grassland area * grassland yield / 2.06

For countries with a productivity above the reference yield of 2.06 tonnes per hectare, the normalized grassland areas are larger compared to the actual areas. This is particularly notable for countries in Central Europe, but also in highly productive tropical countries such as Brazil. In contrast, in countries with very large grassland areas of low productivity such as China or Australia, the normalized grassland areas shrink to less than half of the actual value.

3.3.2 Grassland footprint of Germany and the EU

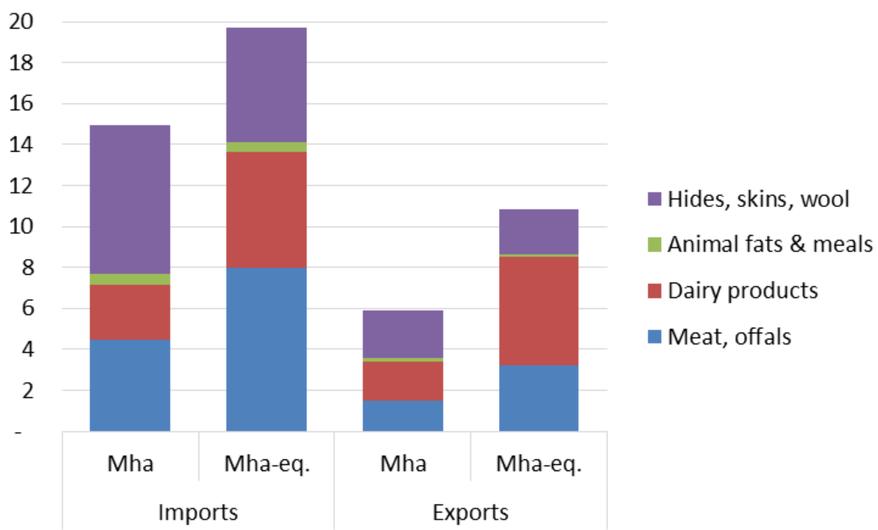
Germany's grassland footprint expressed in normalized equivalent hectares decreased from 1995 to 2010 by 27 % (see Figure 8). This decline is particularly attributable to meat, wool and leather products, while the grassland demand for milk products and animal fats increased slightly. Recently also the grassland footprint for the consumption of meat products rose again significantly from 7.4 Mha in 2005 to 8.6 Mha in 2010. The share of non-food products declined steadily von 34 % in 1995 to 21 % in 2010.

Figure 8. Temporal development of the grassland footprint of Germany, expressed in million normalized equivalent hectares (Mha-eq.), 1995-2010



Via the imports of animal products from ruminants, Germany receives significant amounts of embodied grassland. Figure 9 highlights a strong effect of using normalized equivalent hectares for imports and exports as compared to actual grassland areas reported in FAOSTAT.

Figure 9. Grassland embodied in Germany's external trade, measured in million hectares (Mha) and million normalized equivalent hectares (Mha-eq.), year 2010



Germany's grassland footprint increases for both imports and exports, when moving from the actual to the normalized hectares. Interestingly, the shifts from non-weighted to weighted areas follow different patterns depending on the product group. Grassland areas related to meat and dairy products significantly increase after normalization, indicating that high-productivity grassland areas serve as the production base for these products. In contrast, the grassland footprint for non-food products such as hides, skins and wool decreases from the actual to the weighted perspective. These products therefore tend to stem from lower-productive areas.

Table 5 illustrates Germany's domestic grassland and grassland embodied in foreign trade from the perspective of actual (above) and normalized (below) areas in the year 2010.

Table 5. Grassland footprint, actual areas (above) and normalized areas (below), Germany, 2010

	Domestic production	Net imports	Total Footprint[1]	SRR[2]	Food Footprint	Non-Food Footprint
	in 1000 hectares			*in percentage terms*		
Meat & offal	1,228	2,993	4,221	29 %	92 %	8 %
Dairy products	3,325	736	4,061	82 %	91 %	9 %
Animal fats & meals	36	419	454	8 %	45 %	55 %
Hides, skins, wool	91	4,915	5,005	2 %	0 %	100 %
TOTAL	**4,680**	**9,063**	**13,741**	**34 %**	**56 %**	**44 %**
	in 1000 equivalent hectares			*in percentage terms*		
Meat & offal	3,878	4,743	8,622	45 %	97 %	3 %
Dairy products	10,499	357	10,856	97 %	94 %	6 %
Animal fats & meals	114	347	461	25 %	41 %	59 %
Hides, skins, wool	287	3,456	3,742	8 %	0 %	100 %
TOTAL	**14,778**	**8,903**	**23,681**	**62 %**	**79 %**	**21 %**

1: Domestic production + Net imports = Total Footprint (includes waste in storage and food processing); **2**: SRR (Self-Reliance Ratio) = Grassland in domestic production divided by Footprint

Both Germany's domestic grassland and grassland embodied in foreign trade increase because of the relatively low global mean productivity of 2 tons/ha used for normalization. The grassland footprint measured in normalized hectares is 23.7 Mha-eq. (corresponding to 49 Million tons biomass) compared to an unweighted grassland footprint of 13.7 Mha.

Accordingly, the self-reliance ratio differs depending on the type of area measurement. Normalizing grassland to global mean biomass yields results in a self-reliance ratio of 62 %, i.e. 38 % of the grassland areas are located outside Germany. Based on actual areas, the self-reliance ratio is only 34 %, i.e. two thirds of the grassland is sourced from abroad.

Also the share in the footprint of food (meat, dairy) and non-food products (hides, skins, wool) changes depending on the chosen unit of measurement. The non-food share in the weighted grassland footprint is only 20 % compared to 43 % when the footprint is measured in areas not normalized. The reason for this is the high dependence of the non-food sector on imports from regions where the grassland productivity is lower compared to Germany. In contrast the food-related grassland footprint is primarily sourced from domestic grassland, where biomass yields are significantly higher than on global average.

Over time Germany's grassland in domestic production, grassland footprints in general as well as the difference between weighted and unweighted footprints show a decreasing trend. For the year 1995 Germany shows a grassland footprint of 27.9 Mha-eq. or 13.5 Mha.

For the EU-28, patterns in origin and composition of grassland footprints are similar as those observed for Germany. A major factor is again the strong influence of grassland embodied in imports of hides, skins and wool sourced from countries with yields below the global average (e.g. China, Australia). On average grassland productivity in the EU is significantly higher than those 2 tons/ha. This results in a higher share of the EU's grassland areas in global grassland areas (4.6 %) when measured in normalized equivalent hectares (158 Mha-eq.) as compared to reported actual grassland areas (68 Mha or 2 %). The same applies for net imports and the grassland footprint of the EU, which are 167 Mha-eq. (4.9 %) from a normalized perspective compared to 118 Mha (3.5 %) of actual grassland.

3.4 Forestland footprint

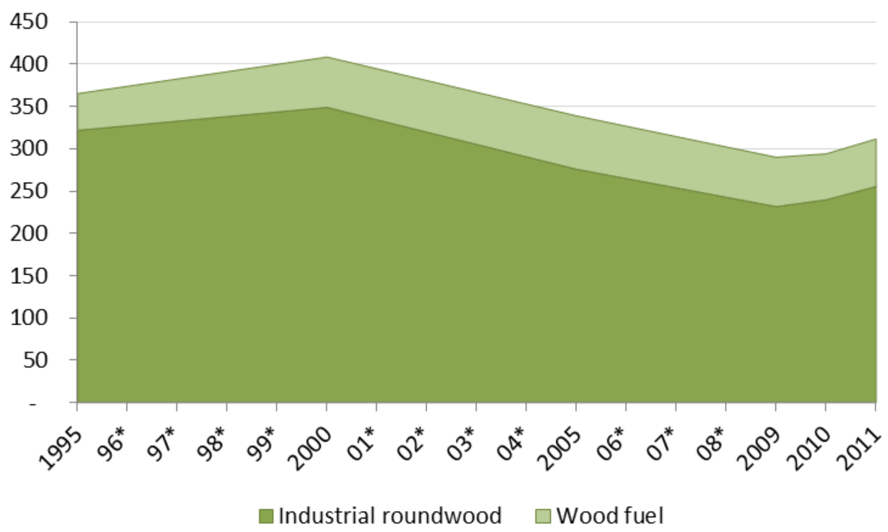
3.4.1 Methodological concept

In contrast to the presented cropland and grassland footprint calculations, where a hybrid accounting method was applied, the forestland footprint results shown below are derived based on MRIO calculations applying EXIOBASE version 3.3. While also for the case of wood products it would be preferable to apply a mixed-unit accounting system, the LANDFLOW model used in this project only covers agricultural commodities.

3.4.2 Forestland footprint Germany and the EU

Figure 9 illustrates the development of the German forestland footprint in the time period of 1995 to 2011. Note that calculations with EXIOBASE were performed in 5-year intervals and years in between (marked with an asterisk) were estimated through interpolating data.

Figure 10. Forestland footprint of Germany, 1995-2011



Note: Values for the years marked with an asterisk are based on interpolation.

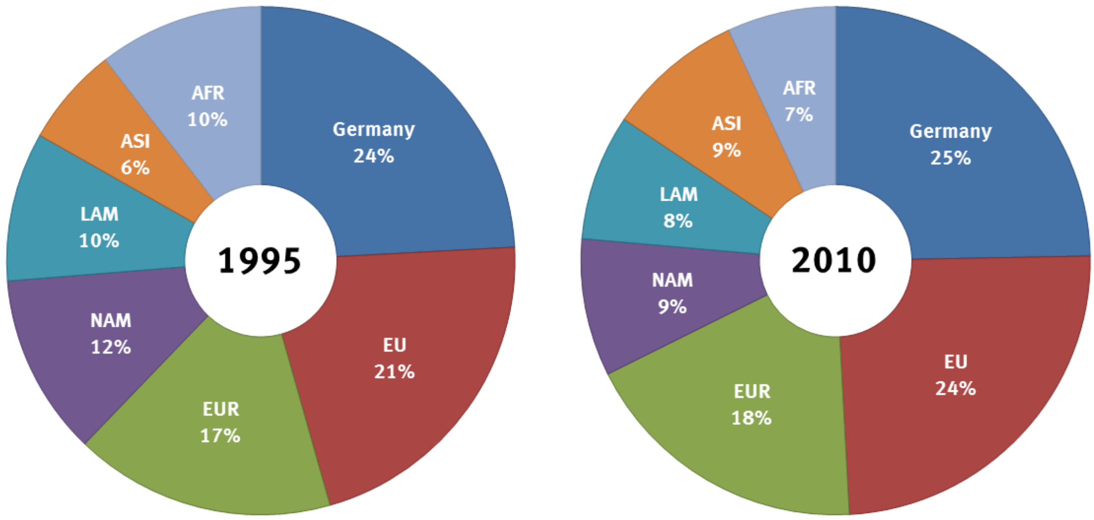
Results reveal significant fluctuations in the overall forestland footprint of Germany. Starting at around 365 thousand km² in 1995, forestland footprint increased to almost 410 thousand km² in 2000, of which 85 % were made of industrial roundwood and 15 % of wood fuel. From 2000 onwards, the forestland footprint declined to around 290 thousand km² in 2009, before turning again upwards. The significant decline by more than 30 % in the period 2000-2009 was driven by all main sectors using wood as a raw material: 'Manufacture of wood and of products of wood', 'Manufacture of furniture', 'Paper' as well as 'Publishing and printing'. Also the direct and indirect inputs of wood into construction activities decreased from the year 2000 onwards.

Moving to the EU28 level, variations in the forestland footprint results could also be observed, although less pronounced. In the year 1995, almost 2.5 million km² were required world-wide to satisfy the final demand for wood and wood-based products in the EU28, with the value increasing to 2.9

million km² in the year 2000. In the period of 2005 to 2009, both types of wood demand decreased significantly, with the footprint dropping particularly in the sectors 'Manufacture of wood and of products of wood', 'Paper', 'Publishing and printing', 'Manufacture of furniture' as well as 'Construction'. At around 2.3 million km², the EU28 forestland footprint remained relatively stable between 2009 and 2011.

As the EXIOBASE model allows specifying the geographical location of timber extraction, the forestland footprint can also be disaggregated by countries and regions. Figure 10 illustrates the composition of Germany's forestland footprint in the years 1995 and 2010.

Figure 11. Geographical composition of Germany's forestland footprint, 1995 and 2010



Note: AFR = Africa; ASI = Asia; LAM = Latin America; NAM = North America; EUR = Europe excl. EU; EU = European Union.

The composition of the origin of the German forestland footprint slightly shifted between 1995 and 2010. While Germany sourced around a quarter of the wood required to satisfy final demand within its own territory across the whole observed time period, the share of imports from other European countries increased from 38 % in 1995 (of which 21 % stemmed from EU countries) to 42 % in 2010 (EU: 24 %). Timber harvested outside Europe decreased its share from 38 % in 1995 to 32 % in 2010, with the Americas contributing the largest non-European amounts of wood.

A similar trend can be observed also on the level of the EU28. Industrial roundwood and fuel wood extracted within the EU28 itself had a share of 54 % in 1995 and increased to 60 % in 2010. Other European countries contributed 18 % and 17 %, respectively. The share of non-European wood that directly and indirectly serves EU28 final demand decreased from 28 % in 1995 to 24 % in 2010.

4 Impact-oriented indicators

4.1 Criteria and key indicators

Area-based land footprint indicators, as introduced in detail in the previous chapter, are powerful tools to illustrate the amount of land areas embodied in internationally traded products and final consumption. However, these indicators, whether expressed in actual or weighted hectares, are unable to measure environmental impacts. Hence, an extended land footprint indicator should focus on qualitative aspects of land use and differentiate between various environmental impacts, in order to address the question on how sustainable the land embodied in human consumption was used. Since the goal is ultimately to use land in a sustainable manner, the land footprint approach must be supplemented with quality and impact-oriented indicators. Note that the term 'impact-oriented indicators' as used in this report not only embraces actual impact indicators but also pressure and state indicators that are suitable proxies for one or more specific environmental impacts.

Report 3 of this project (Fischer et al., 2017b) provides an overview of existing indicator systems for the measurement of the environmental impacts of land use and discussed their linkages and complementary properties to area-based land footprint indicators. Several criteria were defined, which should be fulfilled by impact-oriented indicators used as extensions to area-based footprint indicators:

1. Methods for the calculation of the land footprint attribute observed land use to the primary producing sectors and track the land embodied in goods and services along global supply chains up to final consumption. Therefore impact-oriented indicators need to relate directly or indirectly to primary production, i.e. provide information on impacts related with primary production that can be attributed to a certain crop or animal product or land use activity.
2. In order to express all environmental impacts outside Germany that are associated with German final demand, indicators with global coverage are required. Reliable, high quality and timely data on worldwide environmental impacts are thus a key requirement to calculate impact-oriented land footprints.
3. As the aim is to develop a limited number of impact-oriented indicators, the selected set of key indicators should address environmental issues of high relevance and be able to serve as a proxy for several environmental dimensions.

In consideration of this set of basic selection criteria, a group of experts from German universities and government agencies identified and selected the most relevant impact-oriented indicators during a workshop which was held in Berlin in the frame of this project:

- *Energy use in agriculture*, i.e. on-farm and upstream fossil energy uses, required for fertilizer production (especially nitrogen fertilizer), farm machinery for field operations and other farm equipment, e.g. for drying of harvested crops, water pumps, and heating of livestock stables.
- *Irrigation water use in agriculture*, classified by degree of water scarcity, allowing to accounting for both direct and indirect effects of irrigation impacts on water security and scarcity.
- *Deforestation,* providing insights into the direct and indirect contributions of regional consumption patterns to deforestation worldwide. Deforestation constitutes a powerful proxy for key elements of sustainable land use systems, namely preservation of biodiversity, avoiding CO_2 emissions from loss of vegetation and soil carbon, and safeguarding freshwater resources.

4.2 Deforestation footprint

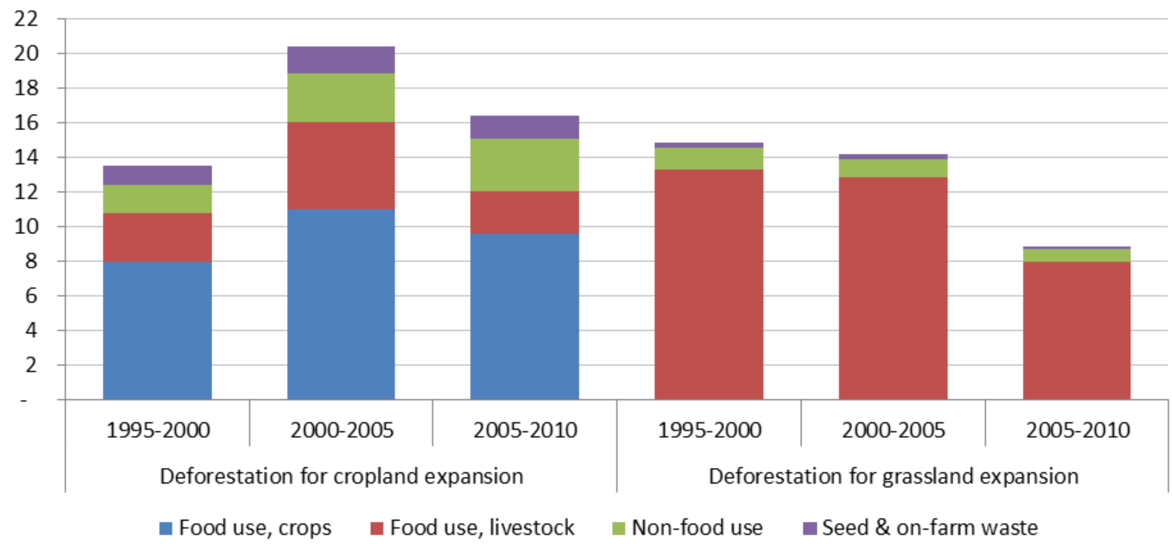
In the project, a quantitative assessment was performed for the third key indicator, i.e. the deforestation footprint. Calculating a deforestation footprint required (a) a spatially explicit quantification of deforestation, (b) a robust method for attributing deforestation to 'responsible' primary sectors, i.e. the crops and livestock products produced on deforested land and (c) a land flow accounting model to track embodied deforestation through the global supply chains (see Chapters 2 and 3 above).

Step b, the attribution of direct and indirect (distant) land use change effects to specific primary sectors, was realised applying the assumption that increases in harvested areas of individual crops or increases in pasture land use were responsible for deforestation in relation to the relative contribution of each primary commodity to agricultural expansion over a given time period. In accordance with reported deforestation data (FAO, 2010), focus was set on three periods of deforestation, namely 1995-2000, 2000-2005, and 2005-2010.

Results illustrate that global deforestation between 1995 and 2010 was more than 200 million hectares. Around 44 % of deforestation can be attributed to the expansion of crop production (51 million hectares of forest loss in 15 years) and to increased ruminant livestock production (38 million hectares), with most of the rest remaining unexplained or being caused by natural hazards. Over the investigated 15 year period deforestation was concentrated in South America (32 % of total), Sub-Saharan Africa (29 %) and Southeast Asia (16 %).

Figure 11 shows the trend in the global deforestation footprint separate for deforestation from cropland versus grassland expansion. The aggregated deforestation footprint peaked between 2000 and 2005 (around 35 million hectares) mainly due to cropland expansion and was lowest (25 million hectares) in the period from 2005 to 2010.

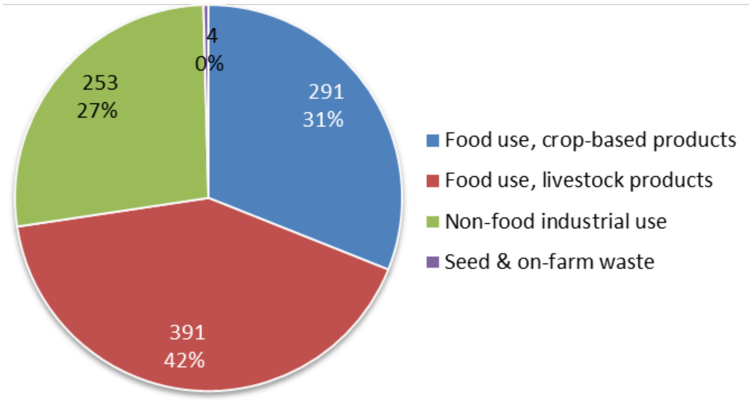
Figure 12. Global deforestation footprint 1995 to 2010, by consumption item, in million hectares per 5-year interval



It can be seen that deforestation for the expansion of cropland was mainly driven by increased production of crops for food purposes and to a lesser extent by the feed production. Across the time period, the non-food industry contributed small but increasing shares of the deforestation footprint. Grassland expansion leading to deforestation was mainly driven by the expanding global demand for animal source foods.

The contribution of Germany's final demand to global deforestation between 1995 and 2010 was estimated to around 940,000 hectares. About three fourth of the deforestation footprint were due to food consumption, mainly from livestock products, and more than one fourth due to the consumption of non-food industrial products (Figure 12).

Figure 13. Composition of deforestation footprint of Germany, 1995-2010 (cumulative), in thousand hectares



Around 90 % of deforestation embodied in Germany's consumption resulted from cropland expansion for food and feed crop production (around 840.000 hectares), the remaining 10 % from pasture expansion and ruminant livestock production (around 100.000 hectares). Important food commodities contributing to deforestation include stimulants (coffee, cacao, tea), meat, dairy products, vegetable oils, and fruit/vegetables/spices. The main non-food products consumed in Germany and causing deforestation elsewhere include commodities produced from vegetable oils, natural rubber, alcohol (ethanol), cotton and other fibres, tobacco, and diverse livestock based non-food products (e.g. hides & skins).

The mean deforestation footprint of every German citizen amounted to 113 m^2 cumulatively over the 15 year period which equals an average annual deforestation rate of 7.5 m^2 per capita. This value is below the global average per capita deforestation of around 140 m^2 over the entire period (9.3 m^2 annually).

Putting these numbers for deforestation in the context of Germany's land footprint (see Chapter 3 above), it can be concluded that – on average – about 1 % of cropland embodied in crops sourced from non-EU countries was deforested.

5 Conclusions

5.1 Achievements of this project

This project provided an important contribution to the very dynamic research field of consumption-based land use indicators and will have an impact far beyond the discussion on environmental and sustainability indicators within Germany alone.

Most notably, the project realised a hybrid land footprint calculation method, which combines the strengths of a robust and highly detailed physical modelling approach with the complementary possibilities that an economic accounting approach can offer. The main strength of this calculation method is that it is globally consistent, i.e. that total global land use exactly equals the aggregated land footprint of all countries and regions worldwide. This is a major strength of top-down approaches compared to bottom-up methods, which apply land intensity coefficients to estimate indirect land requirements of traded products.

By linking a monetary MRIO model to the physical accounting approach, the project allowed performing the first detailed analysis of the land footprint for non-food products, which is the use category showing the highest growth rates and thus being of particular policy relevance. The developed method therefore is suited to inform recent policy strategies focusing on the non-food use of biomass, such as bioeconomy strategies and initiatives launched on the national (German) and international (EU) level.

While the developed land footprint method has clear strengths in particular for comparative assessments on the international level, some important limitations were also observed. As the method requires data with global coverage, data from FAO were the only option to realise calculations with the hybrid method. However, in several areas, FAO statistics may be incomplete or of insufficient quality. Most importantly for the case of Germany, data reported through the FAO for cropland used for fodder crop production differs from those reported by the German Federal Bureau of Statistics. Differences in classification seem to cause a shift between the categories of cropland and grassland of up to 30 % of the respective reported land use.. The outcomes for the German cropland footprint presented in this report thus might be overestimated, especially for the case of animal products, while the grassland footprint might be underestimated. A way to encounter such data issues is described in section 5.2.

The project also realised important steps towards developing impact-oriented land footprint indicators, which complement area-based indicators to illustrate the various environmental challenges and impacts related to different land use practices. The project delivered pilot calculations for the deforestation footprint. In addition, it screened further options to consider a range of different impacts. However, quantitative calculations beyond deforestation proved to be beyond the scope of this project due to the high efforts required for compiling spatially explicit land use impact datasets with global coverage.

The set of proposed indicators of area-based and impact-oriented land footprints provide a very rich data basis for the assessment of policies related to land resources. For example, the EU's Roadmap to a Resource Efficient Europe identifies the issue of an efficient use of limited land resources to meet human demand as one key element and calls for tools to monitor and measure progress on resource efficiency (European Commission, 2011).

The methods developed in this project provide consumption-based land use indicators with a high level of commodity detail. With the proposed method, the extents of land appropriated for different human consumption patterns can be differentiated and made transparent and comparable across countries and regions. The indicators can be used to analyse land footprints and associated environmental impacts, for example, for analysing different dietary patterns, and may serve as one key input for discussing criteria and measures to realise more sustainable consumption patterns.

5.2 Areas for further development

While significant improvements have been achieved in this project, a number of areas for further research remain to be tackled in the future.

This involves on the one hand further improvements of the land footprint accounting methods. One key area here is to achieve a more detailed reporting of countries and commodities. The current modelling framework, while being more detailed than most prior land footprint models, still works on a relatively high level of aggregation. A more detailed physical allocation model should be implemented applying a highly transparent supply and use structure. A resulting physical biomass MRIO table can then be combined with a monetary MRIO table, thus realising a consistent and transparent hybrid (or mixed-unit) IO model with global coverage and high level of detail. In addition to adding detail and transparency, this would also allow the application of analytical tools such as structural decomposition and path analysis in order to further investigate supply chains and developments over time.

Moreover, reliable numbers for the extents of grassland used for grazing ruminant livestock, e.g. from national statistical sources, could greatly improve the robustness of results for the grassland footprint. Also, more detailed reporting of the use of feed and fodder crops for specific livestock categories could replace the current estimation methods. Completeness and robustness of data reported to FAO on the production of fodder crops (e.g. grasses, forages and silages) should be further scrutinized. This requires consistent definitions of variables related to land use and cover type and harmonized reporting to FAO statistics.

In the case of forestland, available land use statistics lack comparability and reliability. The estimation method applied here uses a combination of wood production statistics and the annual net wood increments per hectare of forestland reported by FAO's Forest Resource Assessment (FAO, 2010). Robustness and comparability of calculations of the forestland footprint would highly benefit from reliable international statistics on forestland use and its intensity.

Finally, national applications of the land footprint accounting method developed in this project should also make use of available national statistical data and expertise. As the above illustrated example of contradicting data reported for cropland used for fodder crop production by FAO and StBA shows, the application of an international accounting approach using international data sources entails the risk of discrepancies with national statistical sources. This problem can be overcome by replacing FAO data in certain cases with data from official national trade and agricultural statistics, thus building a 'single-country national accounts consistent' (SNAC) footprint accounting model (Edens et al., 2015). A SNAC model offers the possibility of combining global coverage with full consistency with official national statistics for the country of interest. This helps filling data gaps and avoiding errors from data misinterpretations. Thus it is highly recommendable to scrutinize national data and amend accordingly when implementing a top-down footprint model for the purpose of environmental monitoring or policy impact assessment on the national level.

Concerning impact-oriented indicators, first, it will be useful and important to study in more detail the differences in the effectiveness of using cropland and pasture resources (including their differences in yields) and their meaningful interpretation with regard to land footprints and environmental impacts. This indeed will require the use of more detailed geographical databases beyond country level statistics, and the application of spatial downscaling and modelling methods.

Second, it is recommended to focus future analyses on the sustainability of key sectors of the German land footprint. These include, for example, livestock products, which are by far the largest component of the German land footprint, vegetable oils, which are of particular interest due to the high dependency on imports especially from Eastern Europe, South America and Southeast Asia, and, more generally, the non-food contribution to the land footprint, which showed the strongest increase in land demand in the past 10 years.

Annual updates of the calculations can be done with a time lag of at least four years. Through the use of now- and forecasting methods, as common in economic statistics, the calculations could however be extended to current time or future periods.

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