TEXTE
79/2017

Extending land footprints towards characterizing sustainability of land use

For our Environment

Umwelt Bundesamt

TEXTE 79/2017

Environmental Research of the
Federal Ministry for the
Environment, Nature Conservation,
Building and Nuclear Safety

Project No. (FKZ) 3711 12 102 2
Report No. (UBA-FB) 002497/3,ENG

Extending land footprints towards characterizing sustainability of land use

by

Günther Fischer, Sylvia Tramberend, Harrij van Velthuizen
International Institute for Applied Systems Analysis, Laxenburg

Stephanie Wunder, Timo Kaphengst, Keighley McFarland
Ecologic Institute, Berlin

Martin Bruckner, Stefan Giljum
Vienna University of Economics and Business, Vienna

On behalf of the German Environment Agency

Imprint

Publisher:
Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
info@umweltbundesamt.de
Internet: www.umweltbundesamt.de

/umweltbundesamt.de
/umweltbundesamt

Study performed by:
Institute for Ecological Economics
Vienna University of Economics and Business
Welthandelsplatz 1
1020 Vienna
Austria

Study completed in:
February 2017

Edited by:
Section I 1.4 Economic and Social Environmental Issues, Sustainable Consumption
Michael Golde

Section I 1.5 National and international Environmental Reporting
Stephan Timme

Publication as pdf:
http://www.umweltbundesamt.de/publikationen
ISSN 1862-4804

Dessau-Roßlau, September 2017

Further published reports of research project 3711 12 102 2:
TEXTE 77/2017 Review of land flow accounting methods and recommendations for further development
TEXTE 78/2017 Quantifying the land footprint of Germany and the EU using a hybrid accounting model
TEXTE 80/2017 Development of consumption-based land use indicators – Synthesis report

The project underlying this report was financed by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear safety under project number FKZ 3711 12 102 2. The responsibility for the content of this publication lies with the author(s).

Kurzbeschreibung

Der globale Handel von biomassebasierten Produkten führt zu einer zunehmenden regionalen Entkopplung der Fläche von Produktion und Konsum. Dies erschwert das Aufzeigen der Zusammenhänge zwischen den beanspruchten Flächen und den landnutzungsbedingten Umweltauswirkungen. Die Berechnung des Flächenfußabdrucks zeigt den notwendigen Umfang der für den Konsum benötigten Fläche. Ein weiterer Bericht (Fischer et al. 2016) der vorliegenden Studie beschreibt die Methodik zur Berechnung des Flächenfußabdrucks und Ergebnisse für Deutschland und die EU. Um die Nachhaltigkeit der Landnutzung besser beurteilen zu können, sind weitergehende Analysen, die die Zusammenhänge zwischen den beanspruchten Flächen und den landnutzungsbedingten Umweltauswirkungen abschätzen, nötig. 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.

Vorerst wird ein Überblick zu Indikatoren, die Umweltwirkungen von Landnutzung darstellen und für eine Erweiterung von Berechnungen zum Flächenfußabdruck genutzt werden können, gegeben. Der Bericht diskutiert im Weiteren folgende als besonders relevant identifizierte Schlüsselindikatoren: Systemindikatoren, die 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. Darüber hinaus werden die entwickelten Berechnungsmethoden und -ergebnisse für Systemindikatoren für Grün- und Ackerland und den Entwaldungsfußabdruck dargestellt.

Abstract

The global trade of biomass-based products leads to an increasing regional decoupling of the area of production and consumption. Area-based land footprint calculations attribute the extents of land use required to prevailing national consumption patterns. Another report (Fischer et al., 2016) of the present study describes the methodology for the calculation of area-based footprints and presents results for Germany and the EU. 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.

First, existing indicators for representing the environmental impacts of land use are introduced in the context of their linkages and complementarity to area-based land footprints. The report 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. We introduce the methods developed for the quantification of system indicators for cropland and grassland footprints and for the deforestation footprint, and present results for Germany and the EU.

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Acronyms

AQUASTAT	FAO's global water information system
DM	Dry matter
EU	European Union
EXP	Exports
FAO	Food and Agriculture Organization of the United Nations
FAO-FRA	FAO Forest Resource Assessment
FAOSTAT	Statistics Division of the FAO
FP	Footprint
FP-Cropland	Cropland footprint
FP-Cropland-LQw	Land quality weighted cropland footprint
GAEZ	Global Agro-Ecological Zones Methodology
GHG	Greenhouse Gas
IIASA	International Institute for Applied Systems Analysis
IMP	Imports
IPCC	International Panel on Climate Change
ISCRIC	International Soil Reference and Information Centre
IUCN	International Union for Conservation of Nature and Natural Resources
LULUCF	Land use, land use change, and forestry
MDG	Millennium Development Goals
Mha	Million hectares
MRIO	Multi-regional input-output
NPP	Net Primary Production
OECD	Organisation for Economic Co-operation and Development
PPP	Plant Protection Products
SDG	Sustainable Development Goals
UNEP	United Nations Environment Program
UNFCC	United Nations Framework Convention on Climate Change
WCMC	World Conservation Monitoring Centre

Acknowledgements

The study greatly benefited from discussions and recommendations from the participants of an expert workshop in Berlin in June 2014 (Annex 3).

The project was funded by the German Federal Environment Agency (UBA) through the German Federal Ministry for Environment, Nature Protection, Building and Nuclear Safety (MBUB0 under R&D contract 3711 12 102 2.

1 Introduction

Fertile land areas to produce agricultural and forestry products are globally limited resources. Land footprint indicators connect human consumption with land use and facilitate the analysis and monitoring of global land use. Land footprints describe the extents (i.e actual hectares) of both domestic and international land resources associated with human consumption. A large fraction of a country's land footprint is due to the consumption of products originating from the agricultural and forestry sectors. Increasing population numbers combined with dietary changes have resulted in growing pressure on the Earth's limited land resources (Lambin and Geist 2006).

Area-based land footprints facilitate delineating the "safe operating space" for humanity (Rockström et al. 2009), a key requirement for achieving sustainable land use systems. A methodology review and recommendations for quantified land footprints (Bruckner et al. 2016) and a quantification for Germany's, the EU's and major global economies have been described elsewhere (Fischer et al. 2016).

Land footprints provide important insights into regional heterogeneities of land areas required for different consumption patterns. For example, Germany's food-related footprint for cropland in 2010 was 1980 m^2 per capita, of which two thirds (66%) are due to the consumption of livestock products. In comparison, the global average is 1762 m^2 cropland per capita with 61% required for crop products and 49% for livestock products. Cropland embodied in non-food industrial consumption (e.g. bioenergy, textiles from cotton, fibre, oleo-chemicals from vegetable oil; latex from natural rubber), i.e. the non-food cropland footprint, amounts on a global average to 258 m^2/capita compared to 660 and 557 m^2/capita for Germany and the EU respectively (Fischer et al. 2016).

However, the land footprint as an area-based indicator is unable to illustrate a large number of land-related environmental impacts or to reflect on the quality and productivity of land use. Hence an extended land footprint provides information beyond how much land is embedded in certain products and consumption patterns by also focusing on qualitative aspects of land use and differentiate in terms of environmental impacts, i.e. how sustainable the land embodied in human consumption was used. Since the goal is ultimately to use land sustainably, the land footprint approach must be supplemented with quality and impact-oriented indicators. The aim is to extend the area-based land footprints (Fischer et al. 2016) with indicators characterizing sustainability of land use.

The focus of this project also is to provide an overview and discussion on possible land quality and environmental impact oriented indicators. To place the study in its political context and discuss potential uses of project results, chapter 2 discusses the current role of land-related indicators in international and national policy making. In chapter 3 we describe the study's scope and system boundaries and propose a structure to organize indicators hierarchically. The focus of chapter 4 is on the methodology applied for extending area-based land footprints. Chapter 4 also includes a comprehensive summary of a review of existing land use indicators. Starting from the wider range of potential land use indicators, chapter 5 argues which priority indicators are most suitable for extending land footprints. Eventually, chapter 6 undertakes a first quantification for selected priority indicators with a focus on Germany. Conclusions are summarized in chapter 7.

2 Land related indicators in international and national policy making

To enhance usefulness and applicability in policy making we consider international policy making in the development of indicators.

The most important process currently is the development of sustainable development goals (SDGs). The purpose of SDGs is to address the broad challenges of poverty eradication, environmental protection and sustainable consumption and production. They shall thus set at right the shortcomings and challenges of the UN's *Millennium Development Goals* (MDGs) which expire by the end of 2015. The so called "agreed language" in the Rio+20 outcome document, "*The future we want*", can be an indicator that land will be of importance in the definition of the SDGs: In paragraph 206, the heads of states and governments "*recognize the need for urgent action to reverse land degradation. In view of this we will strive to achieve a land degradation neutral world in the context of sustainable development*".

A beneficial outcome of this process could be a set of concrete goals, targets, and indicators as well as best practice examples of how to implement the SDGs on national and other levels. It remains to be seen if and how the discussion about a land specific goal on "zero net land degradation" will pay out. Currently (as of February 2015), discussions take place on national and international levels among policy makers, NGOs, academia and other stakeholders on how to define indicators for the goals and targets that have been suggested by the United Nations Open Working Group on Sustainable Development Goals in July 2014 (UN OWG 2014). A crucial point will be the question how to integrate land issues into the SDGs and how specific the monitoring / indicator requirements will be.

This international process will likely have consequences also for the national level. In particular, the anticipated update of the *German Sustainability Strategy* with its targets and indicators will need to consider the SDGs that will be finalized by then and need to be applied in developing and developed countries alike.

As an important EU policy the EU *Roadmap to a Resource Efficient Europe* (COM (2011) 571) includes the milestone that by 2020, EU policies are on track with an aim to achieve *no net land take* by 2050. As for the resources "land and soils" it sets the milestone: "By 2020, EU policies take into account their direct and indirect impact on land use in the EU and globally, and the rate of land take is on track with an aim to achieve no net land take by 2050; soil erosion is reduced, and the soil organic matter increased, with remedial work on contaminated sites well underway." It proposes that thematic indicators[1] will be used to monitor progress towards existing targets in other sectors, as detailed in the Staff Working Paper accompanying the Roadmap. It also sets the target to establish a common methodological approach to assess, display and benchmark the environmental performance of products through an environmental footprint (European Commission 2011a; European Commission 2011b).

Moreover, the EU Commission is planning to develop a *land communication* in 2015, discussing also potential land targets and land use related indicators.

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[1] For land use and soil, the EU Commission proposes indicators and milestones for "Reducing the anthropogenic pressure on ecosystems from land take" and proposes the indicator "Average annual land take on the basis of the EEA Core Set Indicator 14" "Land take". Milestone: Annual land take (i.e. the increase of artificial land) does not exceed 800 km^2 per year at the EU level by 2020." The Commission Staff Working Paper also contains indicators and milestones for "Soil erosion", "Maintaining soil organic matter levels" and "Identifying and remediating contaminated sites" (SEC(2011) 1067 final, part II).

Other important policy processes around land use indicators take place within the international processes to develop appropriate indicators for sustainable bioenergy, e.g. the set of indicators developed in the *Global Bioenergy Partnership* in 2011.

Last but not least, the *German program for resource efficiency "ProgRess"* (BMU 2012) is currently focusing on abiotic resources and the material use of biotic resources, but does not cover land and biotic resources as such. It may, however, well include these aspects in the further development of the program, with implications on policies for land use and indicators to assess land use in Germany.

3 Scope and approach

3.1 Project approach towards sustainable land use and system boundaries

Indicators are first and foremost devices to measure progress towards reaching a stated objective. In order to find appropriate impact-oriented indicators in addition to the area-based land footprint approach it is essential to have a clear understanding of the objective of sustainable land use.

This requires an understanding of how sustainable land use and management is defined, and what is the underlying objective of a sustainable land use[2].

The FAO definition of land – developed for the "Framework for Land Evaluation" – provides a concise definition:

> *"Land is a delineable area of the earth's terrestrial surface, encompassing all attributes of the biosphere immediately above or below this surface, including those of the near-surface climate, the soil and terrain forms, the surface hydrology (including shallow lakes, rivers, marshes and swamps), the near-surface sedimentary layers and associated groundwater reserve, the plant and animal populations, the human settlement pattern and physical results of past and present human activity (terracing, water storage or drainage structures, roads, buildings, etc.)."* (FAO 1976)

According to this definition land has a very broad scope encompassing interlinkages with hydrology, biodiversity, near surface climate and soil.

Similarly broad are the nine land functions that the FAO identified (FAO 1995 p.19) and that include many ecosystem services (see chapter 3 for the relevance of the concept of "ecosystem services" for the project approach):

1. *Production function*: land is the basis for many life support systems, through production of biomass that provides food, fodder, fibre, fuel, timber and other biotic materials for human use, either directly or through animal husbandry including aquaculture and inland and coastal fishery (the production function);
2. *Biotic environmental function*: land is the basis of terrestrial biodiversity by providing the biological habitats and gene reserves for plants, animals and micro-organisms, above and below ground (the biotic environmental function);
3. *Climate-regulative function*: land and its use are a source and sink of greenhouse gases and form a co-determinant of the global energy balance – reflection, absorption and transfor-

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[2] The German National Sustainability Strategy – approved in 2002 and further developed regularly ever since – provides a basis for an approach towards sustainability and is the foundation for the understanding of sustainability in this project. Within this strategy, intergenerational equity, quality of life, social cohesion and international responsibility are the centre. However, there is no definition of what "sustainable land use" means in this context, which is why this chapter further explores more detailed definitions.

mation of radiative energy of the sun, and of the global hydrological cycle (the climate regulative function);

4. *Hydrologic function*: land regulates the storage and flow of surface and groundwater resources, and influences their quality (the hydrologic function);
5. *Storage function*: land is a storehouse of raw materials and minerals for human use (the storage function);
6. *Waste and pollution control function*: land has a receptive, filtering, buffering and transforming function of hazardous compounds (the waste and pollution control function);
7. *Living space function*: land provides the physical basis for human settlements, industrial plants and social activities such as sports and recreation (the living space function);
8. *Archive or heritage function*: land is a medium to store and protect the evidence of the cultural history of humankind, and source of information on past climatic conditions and past land uses (the archive or heritage function);
9. *Connective space function*: land provides space for the transport of people, inputs and produce, and for the movement of plants and animals between discrete areas of natural ecosystems (connective space function).

Sustainable land use therefore needs to maintain these functions in the short and long term.
In a brief and more global sense, it can also be expressed as following:

> *"A global sustainable land use serves the needs (for food, energy, housing, recreation etc.) of all human beings living on earth today and in the future, respecting the boundaries and the resilience of ecological systems."* (Kaphengst 2013) [3]

Taken this breadth of land functions into account it becomes apparent that any full set of impact orientated indicators that aim to address sustainability of land use in its broader definition will need to address socio-economic indicators as well.

This project however limits its analysis on impact indicators that can measure environmental impacts of land use only. A brief introduction into potentially relevant socio-economic indicators is included in the Annex 1 of this report.

3.2 Methodology for structuring the indicators

In order to discuss and identify a selected set of priority indicators that are most suitable to extend land footprints, we first provide an overview of available indicators for characterizing sustainable land use.

However, there is currently no structure and set of indicators readily available that directly serves the objectives of this project (see also selection criteria for indicators, chapter 4). Rather, there are different sets of indicators that all have their value in their contexts (e.g. assessments of ecosystem services, environmental impacts, evaluating the bio-economy, indicators for lifecycle assessments etc.) but need to be interpreted further in their potential function as impact indicators for the land footprint. We've therefore developed a project-tailored structure as shown in the Table 1.

With regard to the DPSIR categories of indicators (Driving force, Pressure, State, Impact and Response) as used e.g. by the European Environment Agency [4] this includes land related driver and

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[3] A definition that takes the above mentioned functions into account and was developed in a discussion paper exploring differences between strong versus weak sustainability concepts with regard to sustainable land use.

pressure indicators (land use intensity and land conversion) as state and impact indicators to assess environmental impacts.

Table 1. Environmental impact indicators for sustainable land use

Indicator Category	Sub-Category	Indicator	Proxies /Indicator expressed as
Environmental Impacts	Biodiversity	Abundance and distribution of (selected) species	Abundance of red list species; Abundance of farm birds; Livestock genetic diversity, Mean species abundance; Integrated approach: Biodiversity Damage Potential
		Fragmentation of (semi) natural areas	Effected mesh size, unfragmented low-traffic areas
		Livestock genetic diversity	Number of locally adapted breeds; proportion of the total population accounted for by locally adapted and exotic breeds; number of breeds classified as at risk, not at risk and unknown
		Protected areas	% of protected land
		Landscape diversity	% of structural elements in the area
	Soil	Change in SOC	Change in soil organic carbon (SOC)
		Wind/water erosion	Soil loss (in t/ha/year)
		Soil contamination	Appearance of pollutants above a critical level Area classified as „contaminated site“
		Soil compaction	Bulk density
		Soil salinity	Electrical conductivity of soil
	Water	Water availability/scarcity	% withdrawals to total renewable water resources, Water Exploitation Index, Falkenmark Water Stress Indicator
		Water quality	Biochemical oxygen demand (B.O.D.); pH content, conductivity, Increases in nitrogen and/or phosphorus in natural waters
	Climate	GHG emissions due to land use, land use change and forestry	CO_2 equivalents from LULUCF; Carbon transfers to the air per hectare
Land Use Intensity	Input intensity	Fertilizer use	Total fertilizer use per ha, nitrate or chemical content of (ground) water, Nutrient/Nitrogen balance
		Use of Plant Protec-	Total pesticide use per land unit, Levels of PPP in

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4 To analyse the interplay between the environment and socio-economic activities the European Environment Agency uses the "DPSIR" framework, as a slightly extended version of the "PSR" (pressure–state–response) model used by the OECD.

Indicator Category	Sub-Category	Indicator	Proxies /Indicator expressed as
		tion Products	(ground) water, PPP use compared to max. recommended or allowed levels
		Irrigation use	Share of irrigated land in total cropland
		Energy use in agriculture	Agricultural energy use per ha cropland; Energy for water pumping, machinery; etc.
	Management practices	Agro-diversity	Crop diversity, Crop rotations/frequency of cropping; Field size; Number of weed species in the cultivation area; Area under sustainable management (% of cropland under organic farming; area under agri-environmental payments etc.)
		Grassland management	Livestock /animal units per hectare; Grassland Management frequency
		Forest management	Forestry management systems, Harvest practices (e.g. % clear-cut harvest), Content of deadwood in forests
	System indicators	Yield gaps	Ratio of actual vs. potential yields, Tau-Factor
		HANPP	% of HANPP (Human Appropriation on Net Primary Production) in relation to NPP (Net Primary Production)
		Bioproductivity weighted land footprint	Land footprint expressed in terms of potential cropland productivity (e.g. land footprint weighted by potential cropland productivity)
Land conversion	Primary sectors	Conversion to/from forest land	Gross deforestation; Afforestation
		Conversion to/from cropland	Cropland expansion
		Change in grassland area	Change in grassland area
	Other	Land take /sealing	Built-up land and settlement/infrastructure, Mining areas
		Land restoration	Area rehabilitated; Area restored to natural conditions

Table 1 identifies the most important indicator categories and subcategories for impact-oriented indicators with regard to land use and environmental impacts. Annex 2 further explains all categories and subcategories and provides an introductory section about the relevance for different indicator categories. It also gives an overview about the scope of available indicators, including those that are not further analysed within this working paper.

However, while the list of indicators and proxies show those indicators which are most commonly discussed in the literature and/or applied in practice (e.g. within life cycle assessment, in political strategies etc.) the list is not exhaustive, as in most sub-categories a broad variety of indicators has been developed in various contexts.

In order to specifically highlight the interactions between the goal of sustainable land use and environmental impacts we've developed in Table 2 an evaluation of

a) The most relevant environmental impacts of land use

b) The relevance of each indicator to provide information on provisioning services of land (see box below on “Ecosystem Service Assessments”)

c) The importance of the indicator for enhancing resilience of the land use system.

Table 2: Environmental impact indicators for sustainable land use and their relevance for different environmental goods and provision services

Indicator Category	**Sub-Category**	**Indicator**	**Relevance for sustaining environmental goods**				**Impact on provisioning services**		
			Biodiversity	**Soil**	**Water**	**Climate**	**Food prod.**	**Wood prod.**	**Resilience**
Environmental impacts	Biodiversity	Abundance and distribution of (selected) species	x				x		x
		Fragmentation of natural and semi-natural areas	x						x
		Livestock genetic diversity	x				x		x
		Protected areas	x		x				
		Landscape diversity	x						
	Soil degradation	Change in soil organic matter	x	x	x	x	x		x
		Wind and water erosion	x	x	x		x		
		Soil contamination	x	x	x		x		
		Soil compaction		x	x		x		
		Soil Salinity		x			x		
	Water	Water availability/scarcity			x		x	x	
		Water quality	x		x		x		
	Climate	GHG emissions from LULUCF	x			x			
Land Use Intensity	Input intensity	Fertilizer use	x	x	x	x	x		
		Use of Plant Protection Products	x		x		x		
		Irrigation use		x	x		x		
		Energy use in agriculture				x	x		
	Management Practices	Agro-diversity	x	x			x		x
		Grassland management	x			x	x		x
		Forest Management	x		x	x		x	x
	System indicators	Yield gaps					x		
		HANPP					x	x	
		Bio-productivity weighted land footprint					x		
Land Use	Primary sectors	Conversion to/from forest land	x	x	x	x		x	
		Change in cropland area/	x	x	x	x	x		

Indicator Cate-	Sub-Category	Indicator	Relevance for sustaining environmental goods				Impact on provisioning services		Resilience
Change /Conversion		cropland expansion							
		Change in grassland area	x	x		x	x		
	Other sectors	Land restoration	x	x	x				x
		Land take/sealing	x	x	x	x	x	x	

Indicators to assess "Ecosystem Services" and their relevance for the project approach

Within the last 10 years the concept of "Ecosystem services" has come to a wider attention. It is an important concept as the ultimate goal of a sustainable land use is to sustain ecosystem services and considering that land use change and the loss and degradation of habitats are among the main drivers of ecosystem degradation (Schrotter et al. 2005; Millennium Ecosystem Assessment 2005 in Marques et al.2013).

The Millennium Ecosystem Assessment (2005) defined four categories of services:

1. Provisioning services such as food, water, timber, and fiber;
2. Regulating services that affect climate, floods, disease, wastes, and water quality;
3. Cultural services that provide recreational, aesthetic, and spiritual benefits; and
4. Supporting services such as soil formation, photosynthesis, and nutrient cycling.

Since the definition of ecosystem services within the Millennium Ecosystem Assessment in 2005, there have been many efforts to develop indicators for ecosystem services. The general concept of measuring ecosystem services and the indicators developed for their assessment provide a suitable basis for the project approach described here: For example, indicators that are often used for the assessment of ecosystem services and are also analysed within this project approach are often similar: For provisioning services "food-feed-fibre production" is a frequently named indicator. For regulating services (climate regulation) "carbon sequestration" is often cited and "total amount of soil retained" an indicator for erosion control.

Finally, HANPP (Human Appropriation of Net Primary Production) and NPP (Net Primary Production) indicators can be found in different categories to provide information on primary production, particularly these reflecting harvesting amounts and impacts of land use change. However, ecosystem services indicators are as such not a suitable structure for the overview of indicators within this project as they e.g. include services that go beyond those provided by land (e.g. by marine ecosystems, climate systems) and include cultural services that are beyond the scope of this project.

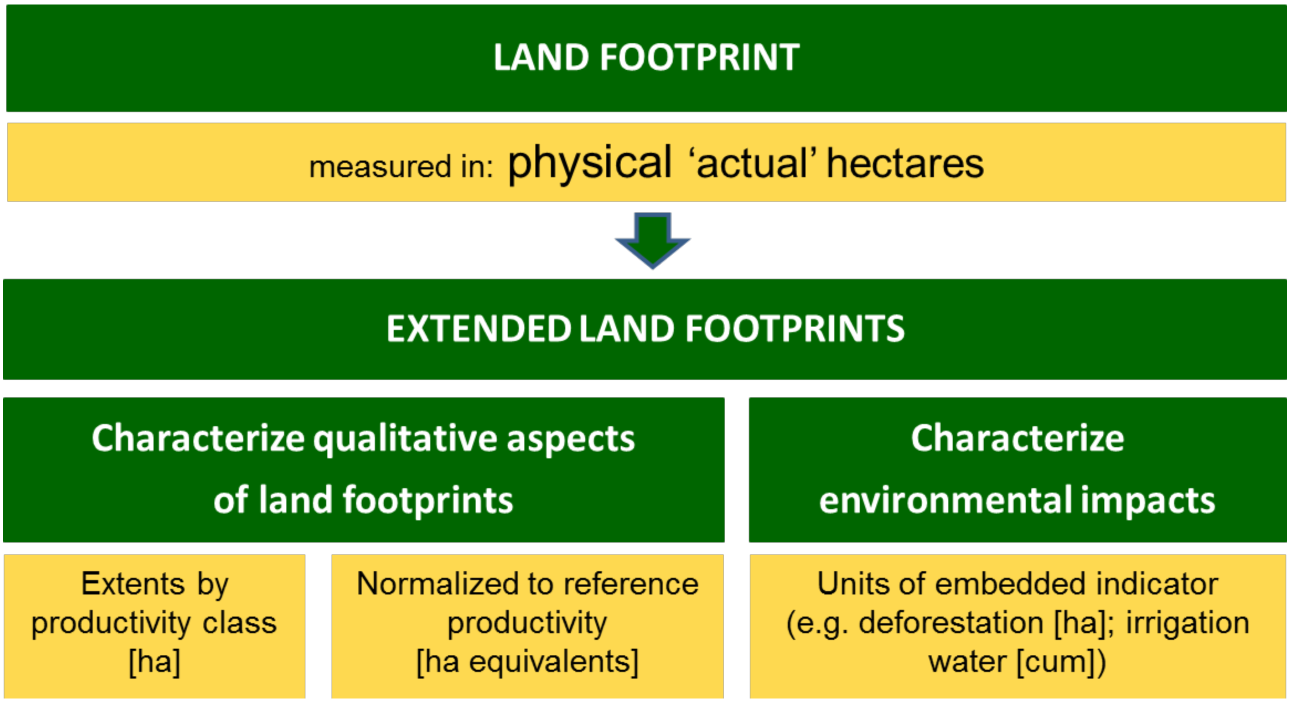
3.3 Basic concepts for extending land footprints

In the context of extending area-based land footprints we alternatively and additionally distinguish two general directions (Figure 1), which

1. concern the quality and effectiveness of use of embedded land resources, and
2. indicate important environmental (and social) impacts and pressures due to involved land use systems.

First, extended land footprints can be based on a characterization of land quality taking into account the spatial heterogeneity of biophysical endowments across regions, which determines biomass productivity of grassland (from lush prairies to paltry pastures in semi-arid environments), crop yields (from triple cropping in year-round producing environments to meagre cultivation on marginal lands) and timber production. These indicators provide a proxy of the human-environment land use systems and have been referred to as 'system indicators' (see Annex 2). They can either be calculated as land footprint area-extents by productivity class or can be expressed as equivalent hectares normalized to a specified reference productivity.

Figure 1: Measurement units of land footprints and their extensions for land quality and environmental impacts



Source: IIASA

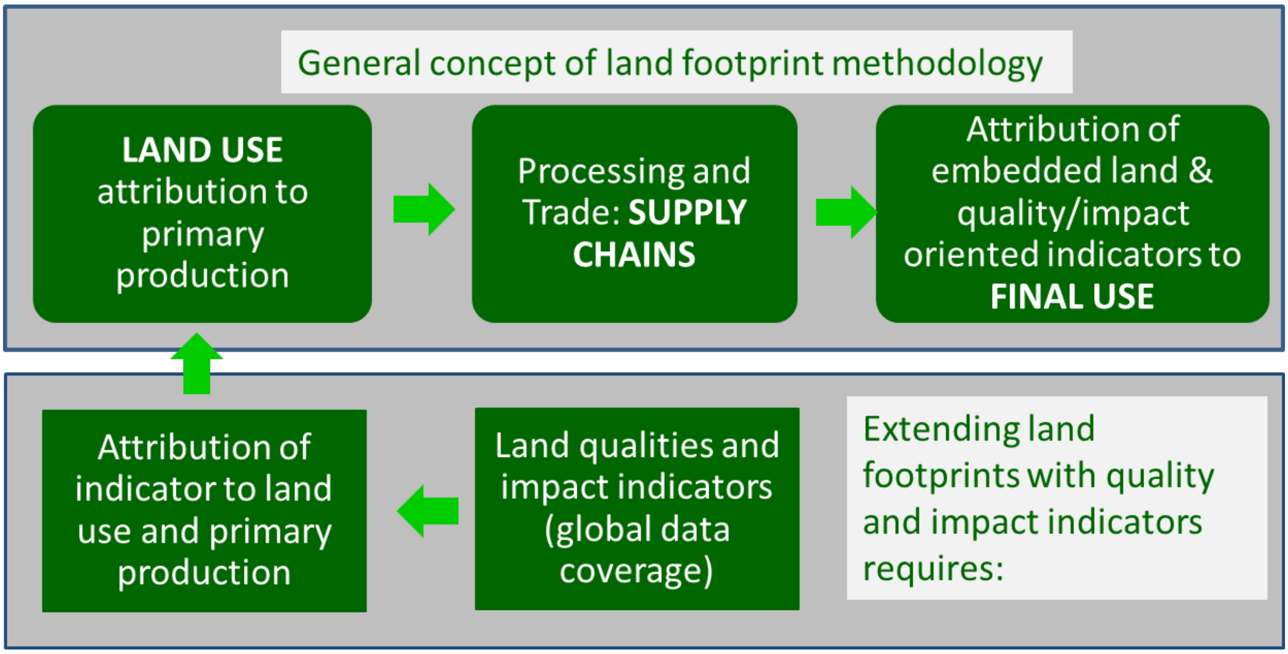
Second, land footprints can be extended by indicators to capture important environmental impacts of land use and to characterize consumption patterns by selected 'embedded' environmental 'goods' or 'bads'. In this case the extended land footprint provides a measure of the respective indicator variable.

Extending land footprints with land quality and impact-oriented indicators entails assessments of land qualities and/or locates specific environmental impacts of primary production where land use and management determine the pressures on ecosystem services. It is therefore necessary to directly link the environmental indicator to land use and primary production (Figure 2).

Primary production here refers to the starting point of the supply chain including

- cultivation of crops on rain-fed or irrigated cropland (e.g. for food, feed, fibre, fuel),
- consumable biomass production of grassland for providing ruminant livestock feed,
- timber harvested from forestland for construction, pulp and paper, wood products and fuel.

Figure 2: Conceptual approach for linking land quality indicators and environmental impacts to land footprints



Source: IIASA

4 Extending land footprints with land quality and impact-oriented indicators

4.1 Selection criteria for possible indicators

The choice of possible impact-oriented indicators that can be used to evaluate environmental impacts and interactions between society (here focused on human consumption and land use) and the environment is very broad. Also, the data availability for indicators significantly differs in coverage, scales and units of measurement – while some data is available per region or country (but not necessarily for all countries worldwide) others are available per ton of a product or in other measurement units.

In the study we make explicit why some indicators are chosen for further analysis within this project while others weren't. The aim is to extend the (area based) land footprint developed by impact oriented indicators. The criteria for the selection process within this project are the following:

I. Usefulness of indicator as basis for evaluation of environmental impact:

   a. We aim for a *limited number* of impact-oriented indicators. Therefore, indicators ideally address environmental issues of *high relevance* and give – directly or indirectly – additional *information on several environmental goods and systems*, i.e. they can function as "*key indicators*". For example, wild bird indicators are not just a way to report wild bird populations but also can give information about the wider environment (Marques et al. 2013).

   b. Even if the overall evaluation of impact-oriented indicators in terms of positive or negative impact on sustainable land use is not within the scope of this project, indicators must provide *clear indications and a solid basis for the evaluation of the global land use-related environmental impacts* associated with a country's consumption. The impact-oriented information needs to be interpretable without ambiguity. For example, a rather clear evaluation is possible for the indicator deforestation (the less deforestation the better) but other indicators might be more difficult to interpret (e.g. use of fertilizer, as the mere amount of fertilizer use does not give information about the impacts e.g. on water pollution).

II. Land footprints attribute observed land use to the primary producing sectors and track the land embedded in goods and services along global supply chains up to final consumption. Therefore from a consumption perspective, impact-oriented indicators need to relate directly or indirectly to primary production, i.e. provide information on production related impacts that can be attributed to a certain primary product and land use. Data on environmental pressures or impacts (e.g. deforestation) therefore needs to be linked with the cultivation of a certain crop, type of livestock supported or biomass harvested (e.g. in the form of deforestation hectares per ton harvested produce).

III. The following aspects are essential for the final selection of indicators in terms of their data availability:

   a. *Availability and quality of global data*: Trade flows are global and individual countries such as Germany import significant amounts of products and embedded resources from many countries. Imported products indirectly importing the land and other resources used to produce these products in the country of origin. Therefore, indicators are needed for which global data is available, in order to express all (environmental) impacts outside Germany that are associated with German demand/consumption. In this study a particular focus is on data availability and quality of data from Germany's most important trading partners.

   b. *Timeliness of data*: In order to provide timely decision support, data need to be available with only short time delays.

   c. *Reliability of data*: To evaluate data quality it is important to use data from well documented sources and to assess critically underlying analytical/ methodological questions of data generation.

Table 3 presents a first estimate of how far each indicator is suitable to match each of the three above-mentioned criteria. The evaluation in Table 3 should be a discussion basis and not aimed at being complete.

Table 3: Sustainability of environmental impact indicators for extending land footprints

Indicator Category	Subcategory	Indicator	Integration in land footprint global supply chain calculations imply:		Usefulness of indicator as basis for evaluation of environmental impacts
			Link to primary production possible[1]	Global data availability[2]	
Environmental impacts	Biodiversity	Abundance and distribution of selected species	3	IUCN, *)	High
		Fragmentation of natural and semi-natural areas	3/4	*)	Moderate
		Livestock genetic diversity	3	FAO	Low
		Protected areas	4	WCMC	Moderate
		Landscape diversity	3/4	?	Moderate
	Soil degradation	Change in soil organic matter	2/3	ISRIC	Moderate
		Wind and water erosion	2/3	*)	Moderate
		Soil contamination	3	?	Moderate
		Soil compaction	2/3	*)	Moderate
		Soil salinity	2/3	*)	High
	Water	Water availability/scarcity	1/4	AQUASTAT	Moderate
		Water quality	3	*)	High
	Climate	GHG emissions from LULUCF	2	UNFCCC	High
Land Use Intensity	Input intensity	Fertilizer use	2	FAOSTAT	Moderate
		Use of plant protection products	2	FAOSTAT	High
		Irrigation use	1/2	AQUASTAT	Moderate
		Energy use in agriculture	2	FAOSTAT	Moderate
	Management practices	Agro-diversity	3	*)	Moderate
		Grassland management	1/2	FAOSTAT	High
		Forest Management	1/2	FAO-FRA	High
	System indicators	Yield gaps	2	*) (e.g. FAO)	Moderate
		HANPP	2/3	*)	Moderate
		Bioproductivity weighted land footprint	2	*)	Moderate
Land Use Change / Conversion	Primary sectors	Conversion to / from forest land	1/2	FAOSTAT; FRA	High
		Change in cropland area / cropland expansion	1/2	FAOSTAT	High
		Change in grassland area	1/2	FAOSTAT	Moderate
	Other sectors	Land restoration	4	?	Moderate
		Land take / sealing	2	*)	High

[1] **Classes in column "link to primary production possible":** 1 = Can be established directly from available data; 2 = Requires additional assumptions and modelling; 3 = Difficult to establish; 4 = Not relevant or related to primary production;

[2] **Global data availability:** *) = Estimates through modelling; ? = Availability not known or not evident

4.2 Summary of a review of existing land use indicators

As there is currently no structure or indicator set readily available that directly serves the objectives of this project, the project team has first worked on a structure that allows a clustering of potential indicators (see Table 1 in chapter 3) and then undertook a screening which indicators are potentially suitable to be used as impact oriented indicators for the land footprint.

We identified three main indicator categories:

1. Environmental Indicators
2. Land Use Intensity
3. Land Conversion

Environmental indicators include the four main environmental categories: Biodiversity, Soil, Water, and Climate/Air.

Biodiversity: Biodiversity plays an essential role to maintain basic ecosystem processes and supporting ecosystem functions (Marques et al. 2013) and changes in biodiversity can influence the supply of ecosystem services. It is widely acknowledged that biodiversity is an important indicator to evaluate the sustainability of land use. However, there is no global, harmonized observation system for delivering regular and suitable data on biodiversity change (Pereira et al. 2013). Moreover, as a rather broad and cross cutting issue biodiversity can be expressed in a wide range of different indicators, which impedes a straightforward and widely applied indicator approach to assess biodiversity across regions. Out of the range of potential indicators we identified the following as potentially suitable indicators:

- Abundance and distribution of (selected) species
- Fragmentation of (semi) natural areas
- Livestock genetic diversity
- Protected areas
- Landscape diversity

Soil: Sustainable land use is closely connected to the sustainable use of soils, essentially constituting the land and basic resources for sustainable land use.

Soils are of high environmental and socio-economic importance due to their manifold vital functions: food and other biomass production, storage, filtration and transformation of many substances including water, carbon, nitrogen. Soil has a role as a habitat and gene pool, serves as a platform for human activities, landscape and heritage and acts as a provider of raw materials.

Therefore, the degradation of soil and land that takes place in large parts of the world is a relevant problem. Soil threats that cause soil degradation – and are therefore relevant entry points for impact-oriented indicators within this project – are: loss of soil organic matter, wind and water erosion, compaction, salinization, landslides, contamination and sealing.

From this range of pressures the loss of soil organic matter – mainly measured in soil organic carbon – stands out as a possible key indicator. Given its relevance for soil functions, biodiversity, climate and productivity , the indicator "change in soil organic matter/soil organic carbon" is frequently recognized as "the best stand-alone indicator for soil quality" (Frischknecht et al. 2013). The loss of soil organic matter is also strongly interlinked with soil erosion – which is another very relevant indicator. Although both soil organic matter and soil erosion are generally suitable impact oriented indicators, global data availability is problematic.

Water: Water availability and quality is essential for agricultural production and agriculture is an important user of water, with 70% of total global fresh and groundwater use is for agricultural purposes (FAO 2011). The unsustainable use of water in agriculture has various external effects and leads to different environmental problems. Overexploitation of water resources can lead to falling groundwater levels and depleted surface waters, which damages associated ecosystems and the services they provide and can lead to conflicts over diminishing water resources. Land use practices also have a large impact on water quality and can lead to losses of biodiversity and degradation of ecosystem services (Srebotnjak et al. 2010). The two relevant indicator categories that need to be considered here are "Water quantity and scarcity" and "Water quality". With the "Water Footprint" there is also a relevant composite indictor available.

Climate: Climate change is among the greatest environmental threats of humanity. Many studies have documented responses of ecosystems, plants and animals to the climate changes that have already occurred. Land use, land use change, and forestry (LULUCF) are major contributors to global greenhouse gas (GHG) emissions, responsible for about 30 % of global emissions, though estimations vary depending on definition and methodology (IPCC 2013).

Land Use Indicators: Land Use Intensity and Land Conversion

The most important direct drivers of biodiversity loss and ecosystem service changes are habitat change (such as land use changes and water withdrawal from rivers with regard to terrestrial ecosystems), climate change, invasive alien species, overexploitation, and pollution (Millennium Ecosystem Assessment 2005). Habitat change both due to land conversion and non-sustainable land use management therefore constitutes an important impact category.

Land Use Intensity: Appropriate indicator subcategories for land use intensity as identified through the project are:

- *Input intensity* (expressed through the indicators: fertilizer use, use of plant protection products, irrigation use, energy use in agriculture)
- *Management practices* (expressed through the indicators: Agro-diversity, Grassland management, Forest management)
- *System indicators* (expressed through the indicators: Yield gaps, Human appropriation of Net Primary Production (HANPP) and bioproductivity weighted land footprint)
  System indicators connect potential and actual productivity indicators, hence give information about aggregated effects of land use intensity. They relate the inputs or outputs of land-based production to system properties e.g. yield gaps (actual versus potential yield), human appropriation of net primary production (HANPP), or wood to wood increment ratios. Limitations towards system indicators however remain as higher intensification rates do not always lead to higher production and high production is not necessarily achieved in a sustainable way so that complementary indicators are necessary to achieve meaningful evaluations (For more information on System Indicators see Annex 2). Bioproductivity weighted footprints provide an indicator for a basic provisioning service of ecosystems, namely biomass productivity, taking into account that the amount of biomass supplied by a hectare of land differs significantly across land use types and ecosystems.

Land Conversion

Land use change is a major driver of land degradation, greenhouse gas emissions (e.g. through deforestation, drainage of peatlands etc.) and biodiversity loss (conversion of natural land/grassland into arable land etc.). The damages of land use change are largest for land use types which are difficult to restore and need extremely long to develop, e.g. thousands of years and more for primary forest and peatbog (Koellner and Scholz 2008).

Appropriate indicators that have been identified for this category are:

- Conversion to/from forest land,
- Conversion to/from cropland,
- Change in grassland area and
- Land take /sealing, Land restoration.

The full screening is documented in Annex 2 of this report. It includes an overview about the scope of available indicators for each indicator category as well as the main characteristics and data requirements per indicator. The priority indicators for extending land footprints are further described in chapter 5.

4.3 Recommendations from an Expert Workshop

The screening of proposed indicators shows that there are no "perfect" indicators yet that meet all selection criteria. It is therefore crucial to make a selection of indicators that together can provide information about a broad spectrum of relevant aspects. This process started with an international expert workshop in Berlin, June 25, 2014.

With 20 experts from international research institutions, NGOs and policy makers the proposed indicators and their potential use for extending land footprints were discussed (Annex 3). Key messages from the expert workshop are summarized below:

- The presented indicator list (Table 1-3) is sufficiently comprehensive for characterizing sustainability of land use.
- The following indicators of high relevance as proxy for sustainable land use have been suggested for further consideration:
    - Environmental impacts: soil organic matter, biodiversity, water availability and quality
    - Land use intensity: system indicators, energy use in agriculture, agro-diversity
    - Land use change/conversion: forest loss, wetland loss, grassland to cropland conversion

For several of these high priority indicators participants stated that limited data availability and methodological difficulties in attributing indicator-values to primary production prevent their use in land footprint accounting procedures. Data limitations were acknowledged regarding changes of soil organic matter content, status and loss of biodiversity, water quality, and wetland loss.

Participants also noted that some relevant indicators have already been assessed and are available from elsewhere (e.g. such as embedded greenhouse gas emissions, virtual water content, etc.). They were therefore given low priority for implementation in this study ("don't reinvent the wheel").

There were controversial opinions expressed in the workshop how indicators dealt with in other political processes (e.g. climate, biodiversity) should be considered for 'extending' land footprints or if it should rather be trusted that these aspects are better dealt with in these processes that put a focus on single aspects.

Relevance of indicators for informing and supporting policies to achieve sustainable land use should be a guiding principle in the ranking of indicators for further research and quantification.

4.4 Challenges and current limitations

Meaningful attribution of land quality and environmental impacts to primary production entails using *data of appropriate scale and resolution* across all areas where primary production occurs. Thus from a consumption footprint perspective it would be necessary to associate primary production (e.g. grazing or maize cultivation) with the respective environmental impacts (e.g. soil erosion, soil organic matter loss, deforestation). Ideally such linkages can be established directly from available data.

However, environmental impacts are often not monitored across larger areas or uniquely associated with one cause. Therefore additional assumptions and modelling may be required for attributing land qualities or the environmental impacts to primary production.

For example, in the case of land degradation, both location and amount of soil loss are required for linking it to primary production. Land degradation however has been mapped using remotely sensed data for hotspots only (Bai et al. 2010). The only global assessment, the Assessment of Human-induced Soil Degradation (GLASOD[5]) (Oldeman et al. 1990) uses an expert-based approach for delineating areas where specific types of degradation are dominating.

In addition methodological attribution challenges may occur. For example, polluting effects of mineral fertilizer application are widely documented. However, not fertilizer application per se, but excess application and nutrient loss causes detrimental environmental effects such as soil contamination and water eutrophication. Each country reports annual fertilizer consumption (e.g. FAOSTAT). A meaningful attribution of national mineral fertilizer application to individual crops and areas including determination of excess application is challenging and requires additional assumptions on e.g. management practices.

In some cases it is conceptually difficult to establish a link between key indicators of sustainable land use and specific primary production. Examples include biodiversity, extents of protected areas, fragmentation of natural habitats, agro-diversity, soil contamination or water quality. For instance, while agriculture is a major cause of decreasing biodiversity, an attribution to individual primary commodities (i.e. crops) is not easily possible.

5 Priority indicators for extending land footprints

The selection of priority impact indicators for extending area-based land footprints builds on the screening of potentially available indicators that has been presented in chapter 4 of this report and in more detail in Annex 2, taking into account the selection criteria for indicators that are also presented in chapter 4. Finally, the selection also builds on the recommendations and discussions of the expert workshop.

This set of different indicators seems to be a meaningful combination of key indicators to provide insights into the nexus of national consumption patterns, land use domestically and abroad and environmental impacts.

5.1 System indicators

5.1.1 Cropland footprint weighted by potential cropland productivity

Population increase and economic development requires by 2050 a 60 percent higher global agricultural production compared to 2005/2007 (Alexandratos and Bruinsma 2012). Sustainable intensification and resource efficient production of agricultural commodities from current cropland is key for developing sustainable land use systems. Also, decoupling of economic growth from natural resource use and its environmental impacts are needed – a need that is also recognized as a central objective of the “Roadmap for a Resource Efficient Europe” (CEC 2011a) developed under the “A resource-efficient Europe” flagship initiative of the Europe 2020 strategy (CEC 2011b).

Production efficiency and the closure of yield gaps therefore play a prominent role and are considered to be a fundamental pillar of a key set of indicators to extend the land footprint. FAO has calcu-

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[5] see http://www.isric.org/projects/global-assessment-human-induced-soil-degradation-glasod

lated a 'yield gap' by comparing current productivity with what is potentially achievable assuming that inputs and management are optimized in relation to local soil and water conditions (FAO 2011).

The achieved production efficiency ('yield gap') at location specific bio-productivities of available natural resources is a comprehensive indicator for the resource efficiency of cropland use.

Cropland productivity depends on the biophysical characteristics of the land (climate, soil, and terrain), farmers' access to technology and agro-research knowledge through extension services, availability of agro-inputs, the land management applied, and on socio-economic circumstances[6].

Land footprints calculate extents of cropland associated with domestic consumption of a country by adding land used for domestic production and land embedded in imported products less land embedded in exported products. The "cropland footprint weighted by potential cropland productivity" extends the purely area-based "land footprint" by applying location specific weights of potential cropland productivity relative to average cropland productivity. Thus the "cropland footprint weighted by potential cropland productivity" is affected by both the specific bio-productivity of a country's resources and the achieved production efficiency. This requires:

1. Spatially detailed estimates of potential cropland productivity. A spatial unit could for example be a country, requiring estimation of average sustainable bio-productivity of cropland (e.g. derived from crop production models and separate for current irrigated and rain-fed land).
2. A robust method for determining the sustainable land production potential. For example, in each location the 'best' performing crop, from a set of globally important crops, can be chosen to define the respective crop production potential. The resulting value can be normalized, for instance by the average potential productivity of global cropland in a target year.
3. Land flow accounts to track embedded bio-productivity weighted land extents through the supply chain.

The "cropland footprint weighted by potential cropland productivity" of a country will be smaller than its (unweight) land footprint when consumption is sourced from land where production is efficient and yield gaps are small. Vice versa, when a country consumes significant amounts of commodities from areas where actual cropland production is well below the sustainable potential, the weighting of the land footprint by potential cropland productivity will increase a nation's footprint relative to other countries. For example, it is well known that many African countries today produce below their sustainable crop production potential resulting from limited access to agricultural input (especially phosphate fertilizer). Weighted cropland footprints of consumption sourced from such regions will thus increase relatively compared to an assessment using unweighted land footprints.

Similarly, when consumption is from regions with higher bio-productivity potential compared to global average the "cropland footprint weighted by potential cropland productivity" will increase relative to the (unweighted) land footprint and will decrease when products are sourced from regions with lower biophysical productivity. Note that the treatment of irrigated land plays an important role in this context. For example the potential cropland productivity in China, where more than half of cropland is irrigated, is significantly higher when bio productivity is calculated for both rainfed and irrigated conditions.

Crop production models estimate the biophysical yield potential of producing a certain crop in a specific location. For example, the Global Agro-Ecological Zones (GAEZ) assessment (IIASA/FAO 2012) provides spatially detailed information on potential land productivity based on climate, soil, terrain data and assumptions on requirements for sustainable management under different levels of agricul-

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[6] For instance in Sub-Saharan Africa limited access to agricultural input (especially fertilizer) is believed to be a main cause for prevailing low crop productivity, which is significantly below the land's biophysical potential.

tural inputs. It also provides an account of current rain fed and irrigated cropland at the grid-cell level consistent with statistically recorded cropland extents in each country.

5.1.2 Grassland footprint weighted by biomass productivity

Similarly to cropland productivity, grassland productivity also varies widely across regions ranging from highly productive grasslands in South America or Central Europe to marginal conditions in semi-arid regions in Central Asia or the northern parts of the Sahel. As a large fraction of global human land appropriation is related to grazing areas, this underlines the need for extending land footprints beyond area-based indicators.

Following the above described principles for cropland, grassland footprints can be normalized relative to the potential biomass productivity in specific locations. For this purpose, spatially detailed grassland productivity data (e.g. GAEZ[7]) are required for the estimation of average grassland yields, e.g. per country, which are then normalized to defined "reference yields". The latter can either be a global average grassland yield or any defined grassland productivity.

For example applying a reference grassland productivity of five tons per hectare (average of Central Europe), then instead of reported 3400 million hectares of grassland, only an equivalent of 1400 million hectares reference grassland is globally available.

5.2 Energy use in agriculture

Prior to the industrial revolution, the primary energy input for agriculture was derived directly from the sun[8]. Industrial agriculture today relies to a significant extent on energy derived from fossil fuels. Agricultural fossil energy inputs are 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, heating of livestock stables.

Amounts of on-farm fossil energy uses are important in the context of climate-smart agriculture. In 2012 FAO and the European Union launched a special program on "Climate-Smart Agriculture: Capturing the synergies among mitigation, adaptation and food security"[9].

Historically on-farm fossil energy input has been an important factor for intensifying the food provisioning services of land, e.g. by using chemical fertilizer, machinery and irrigation. At the same time it has been contributing to climate change by increasing the agricultural sector's GHG emissions.

"Energy use in agriculture" requires data on energy inputs used for primary agricultural production activities. In addition energy input is required along the supply chain (i.e. from farm gate to table) for processing and transport of primary and derived commodities. As the objective of this study is to describe indicators in relation to sustainable land use, we confine our discussion here to fossil energy used in primary agricultural production.

In general, amounts of energy used for producing primary agricultural commodities can be determined in a top-down or bottom-up approach. The former will use available data of energy used in agriculture (usually by country) and disaggregate those to individual primary commodities. This requires formulation of assumptions on how to best disaggregate, e.g. using data on crop type or correlations with fertilizer use. A bottom-up approach seeks to compile data for the main components of agricultural energy use:

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[7] The IIASA/FAO Global Agro-Ecological Zoning databases (IIASA/FAO 2012) include grid-cell based grassland productivity data.

[8] Photosynthesis enabled plants to grow, and plants served as food for livestock, which provided fertilizer (manure) and muscle power for farming.

[9] see www.fao.org/climatechange/epic/home/en

1. fossil energy use for machinery (for transport and harvest)
2. energy embedded in application of chemical fertilizers, especially synthetic nitrogen, an energy intensive produce
3. energy use for irrigation (mainly in the form of electricity)
4. energy used for other on-farm activities (mainly crop drying and heating of stables)

Thus data are required for chemical fertilizer use, machinery, irrigation, crop type, livestock production system (whether confined and in which climate) as well as respective coefficients for energy use (e.g. GJ per kg fertilizer).

FAO has processed and compiled data on both energy use and agricultural production at international level (FAO 2000). FAOSTAT reports in the domain "Agri-Environmental indicators" time series (since 1992) for annual agricultural and forestry energy use, expressed as percentage of a country's total energy use. Energy use from agriculture only (but including fisheries) based on data from the International Energy Agency were used for the calculation of GHG emissions in a recent FAO study (Tubiello et al. 2014). However, the underlying energy data were not published.

In the domain "Emissions Agriculture / Energy use" FAOSTAT reports "Consumption in Agriculture" for various items including 'Electricity', 'Energy for power irrigation', 'Gas-diesel oils' and 'Hard coal'. However, all data in this domain are flagged as 'Unofficial figure' or 'Calculated data'. It should be noted that these figures do not include indirect energy use from applied fertilizer and pesticides.

Eurostat reports the "Total energy use at farm level, in GJ per ha per year" and the "Annual use of energy at farm level by fuel type (GJ/ha)". The OECD has recently published the "OECD compendium of Agri-environmental indicators" (OECD 2013), which includes data on on-farm energy consumption.

In summary, a top-down approach is less data-intensive, but it requires numerous assumptions and depending on the accuracy of the estimates, the compilation of new data. In addition it is important to understand the precise definition of reported energy uses in agriculture. For example, aggregate figures (of e.g. FAOSTAT) do not include indirect energy uses from fertilizer and pesticide production. Especially the extraction of land-based agricultural activities from data like "Energy used in agriculture and forestry (expressed as percentage of total use)" or "Energy used in agriculture including fisheries" requires sub-sectoral data. A bottom-up approach is more accurate, yet data compilation may be challenging, as global national data are not readily available.

5.3 Irrigation water use in agriculture classified by water scarcity/security

Water, in many regions a scarce resource, is a critical production factor for the agricultural sector. Irrigated agriculture has been continuously expanding and today accounts for 20 percent (year 2010) of global cropland (FAOSTAT) and produces as much as 44 percent of total crop production (Alexandratos and Bruinsma 2012).

There is extensive literature on water footprints[10] (defined as the total volume of fresh water that is used to produce the goods and services consumed in individual countries) and virtual water flows, i.e. the volume of water being transferred between two geographically delineated areas as result of product trade (Hoekstra et al. 2011). Water footprint calculations commonly combine green and blue water footprints. The former refers to the part of precipitation that evaporates or transpires through plants, the latter is surface and groundwater applied in irrigated agriculture.

A critical indicator for land use systems is whether the water used for plant production is obtained from water secure or water scarce areas. Water security has been described as a tolerable water-

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[10] see e.g. www.waterfootprint.org

related risk to society (Grey et al. 2013). To be water secure, an individual needs about 1200 m^3 / (cap*yr) (Allan 2010), but strong economies can afford to import water-intensive commodities (Falkenmark 2013).

The Rio+20 conference concluded that, "unless action is taken now, water insecurity is likely to become a key geopolitical issue that affects the entire global economic system" (Rio+20, 2012). By 2025, 1800 million people are expected to be living in countries or regions with "absolute" water scarcity (<500 m^3 / (cap*yr)), and two-thirds of the world population could be under "stress" conditions (between 500 and 1000 m^3 / (cap*yr)) (FAO 2013).

While economic rain-fed agricultural production (using green water) tends to be concentrated in water secure regions, irrigated agricultural production is often located in water scarce regions. Where water withdrawal for irrigation overexploits renewable ground- and surface water resources and is in competition with other sectors and natural flow requirements, the sustainability of land use is endangered.

Ridoutt and Pfister (2009) have addressed the unsustainable use of global freshwater resources by incorporating a characterization of water stress in water footprint calculations of individual product life cycle assessments.

Following this logic of incorporating water scarcity and recognizing the specific importance of irrigated crop production, we propose a hierarchic water indicator including the amount of irrigation water used for consumption (measured in m^3) and a sub-indicator, which determines whether irrigation water is sourced from water secure (abundant) or water scarce areas. This requires:

1. Differentiating primary agricultural production in rain-fed and irrigated production
2. A classification of irrigated areas in terms of prevailing water scarcity, which can be attributed to primary agricultural production
3. Land flow accounting to track embedded irrigation water volumes by water scarcity class through the supply chain

Accounting for both direct and indirect effects of irrigated production impacts on water security/scarcity entails attributing individual irrigated crops to water security/scarcity indicators of larger regional units, e.g. the entire country.

Delineating rain-fed and irrigated production

The demarcation of rain-fed and irrigated crops requires downscaling procedures to allocate reported harvested areas of individual crops to available land use and irrigated area datasets. The FAO/IIASA GAEZ assessment (IIASA/FAO 2012) includes a global inventory of downscaled primary production of major crops consistent with reported national statistics for the year 2000 and 2005 (GAEZ version 3 [11]) and separate for rain-fed and irrigated cropland.

Defining water scarcity and security

The concept of water scarcity is complex to be defined as it implies different dimensions or facets. First, scarcity needs to be understood as a relative concept, i.e., an imbalance between "supply" and "demand" that varies according to local conditions. Second, water scarcity is fundamentally dynamic. It intensifies with increasing demand by users and with the decreasing quantity and quality of the resource. Water scarcity may however decrease when appropriate response options are put in place (FAO, 2013 [12]).

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[11] GAEZ is currently being updated to version 4, which includes downscaled actual crop production for the year 2010.

[12] FAO WATER Topic Water Scarcity: http://www.fao.org/nr/water/topics_scarcity.html

A widely used simple indicator for population growth and finite water resources is the water crowding indicator (Falkenmark et al. 1989a,b, 2007) and its reverse, the per capita available renewable water resources (often referred to as "Falkenmark Water Stress Indicator"). They relate the maximum theoretical yearly amount of water available for a country to population. Defining thresholds related to water scarcity for these indicators is complex as it involves assumptions on water use and water use efficiency.

Water crowding is defined as the ratio of population over annual 'actual renewable water resources'[13]. Water management tends to get stressful around 600 people / (10^6 m^3 * yr) and difficult around 1000 people / (10^6 m^3 * yr) (Falkenmark 1986). For the per capita available renewable water resources it has been proposed that when annual per capita renewable freshwater availability is less than 1700 m^3, countries begin to experience periodic or regular water stress. At levels between 1700 and 1000 m^3 per person per year, periodic or limited water shortages can be expected. Below 1000 m^3, water scarcity begins to hamper economic development and human health and well-being (Falkenmark and Lindh 1976).

Human use of available water resources includes agriculture (irrigation), industry, energy generation and households. Also water must be reserved as 'environmental flows' (Smathkin 2008) required for protecting aquatic ecosystems[14]. The intensity of human uses of finite water resources generally measures water use to availability ratio. It describes demand-driven scarcity and is often referred to as water stress (Kummu and Varis 2011). The UN (UN 1997) has set the withdrawal of 40% as the threshold for situations of high water stress. Almost 2 billion people live in countries where water use exceeds 40% of water availability. This includes India where the 40% threshold has just been reached. In many of these water scarce countries the bulk of water is used in agriculture.

The International Water Management Institute (IWMI) introduced the concept of physical and economic water scarcity (Molden 2007). Physical water scarcity is used to define situations where insufficient water is available to meet all demands including water needed for maintaining aquatic ecosystem services, while economic water scarcity is caused by lacking infrastructure capacity for using available water resources.

Recently frameworks focus on defining water security rather than water scarcity and include consideration of societies' adaptation or coping capacity to water related challenges. Grey et al. (2013) perceived water security from a risk-science perspective and categorized countries and regions into four quadrants in terms of i) complexity and risk of the hydrological system and ii) the level of investment for water risk reduction. IIASA's Water Futures and Solutions Initiative[15] applies for its scenario analysis a hydro-economic classification of countries and watersheds determined by a combination of the economic-institutional coping capacity and hydrological complexity. In this way countries and water sheds can be classified into different categories of hydro-economic development challenges.

Proxies for economic-institutional coping capacity include GDP per capita, the Corruption Perception Index published by Transparency International or the Worldwide Governance Indicators (Kaufmann et al. 2010) published by the Worldbank. Hydrologic complexity is defined by a compound indicator

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[13] Actual renewable water resources (ARWR) is the sum of internal and external renewable resources, taking into consideration the quantity of flow reserved to upstream and downstream countries through formal or informal agreements or treaties, and reduction of flow due to upstream withdrawal; and external surface water inflow, actual or submitted to agreements. ARWR does not include supplemental waters (desalinated, or treated and reuse).

[14] About 25-50% of the mean annual river flows needs to be allocated to freshwater-dependent ecosystems to maintain "fair" ecological conditions (Smathkin 2004; Pastor et al. 2013). Variable flow regimes such as the Nile have lower environmental flow requirements (12 to 48% of mean annual flow) than stable tropical regimes such as the Amazon (30 to 67% of mean annual flow) (Pastor 2013).

[15] see http://www.iiasa.ac.at/web/home/research/water-futures.html

comprising (i) total renewable water resources per capita as a measure of water availability, (ii) the ratio of total water withdrawal to total renewable water resources availability as a proxy for relative intensity of water use, (iii) the coefficient of variation over 30 years of monthly runoff as a proxy for both inter- and intra-annual variability of water resources and (iv) the share of external (from outside national boundaries) to total renewable water resources as a measure for the dependency of external water resources.

Data sources

The UN-FAO AQUASTAT database[16] reports country information of water related variables required for calculating the above indicators. AQUASTAT compiles annual data per country. However, it should be noted that many variables (e.g. water use) are available for selected years only.

Global hydrologic models calculate time series of diverse hydrologic variables including runoff and discharge by grid-cell (usually 0.5 degree longitude/latitude; i.e. about 50 by 50 km at the equator). These hydrological variables are required for estimating inter-annual variability, an important component of hydrologic complexity. Recent results of historical and future time periods from several global hydrologic models are included in the databases compiled by the ISI-MIP project[17].

The World Resources Institute's AQUEDUCT global water risk mapping tool[18] provides selected indicators that measure the underlying factors driving water-quantity related risks across countries and river basins (Gassert et al. 2013).

In conclusion, the proposed indicator requires a delineation of irrigated production, an agreed definition on water security (or water stress) and their respective implementation for primary crop production. Water security can be applied to both rainfed and irrigated production.

5.4 Forest loss (Deforestation)

Forest ecosystems are a central component in the Earth's biogeochemical systems and play a significant role in the global carbon cycle with significant impact on climate change. They are important refuges for terrestrial biodiversity and a source of ecosystem services essential for human livelihood and well-being. More than three quarters of the world's accessible freshwater comes from forested catchments (MEA 2005 Ch.21).

Recent forest loss has been highest in the tropics. Between 1990 and 2005 the highest net forest loss occurred in South America amounting to some 3.3 million hectares annually, followed by Africa with a loss of 1.6 million hectares (FAO and JRC 2012). Between 2000 and 2012 Brazil's slow-down in deforestation was offset on the global level by decreasing forest resources in Indonesia, Malaysia, Paraguay, Bolivia, Zambia, Angola, and elsewhere (Hansen et al. 2013).

Main aggregate proximate causes of tropical deforestation include agricultural expansion, wood extraction, and expansion of infrastructure (Geist and Lambin 2001). Agents of tropical deforestation changed over time. From the 1960s to the 1980s, small-scale farmers, often with state assistance, deforested large areas in tropical Southeast Asia and Latin America. During the 1980s well-capitalized farmers and loggers producing for consumers in distant markets became more prominent in deforestation of lowland rainforests of Brazil and Indonesia (Rudel et al. 2009).

Meanwhile there is growing awareness of the tele-connections between consumer demand in wealthy countries, global supply chains and the loss of some of the world's last remaining intact and bio-

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[16] http://www.fao.org/nr/water/aquastat/main/index.stm

[17] https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip

[18] see http://www.wri.org/our-work/project/aqueduct

diverse forest ecosystems. In response a number of initiatives has emerged to de-couple economic growth and consumption from forest loss (Brown and Zarin 2013). In 2008, EU environment ministers pledged to pursue the goal of halting global forest loss by 2030 and at least halving tropical deforestation by 2020, compared to 2008 levels[19].

Extending land footprints with a deforestation indicator, i.e. developing an analogous "deforestation footprint", provides revealing insights into regional consumption patterns contributing directly or indirectly to deforestation. It constitutes a powerful proxy for key elements of sustainable land use systems, namely preservation of biodiversity, avoiding CO_2 emissions from lost vegetation and soil carbon, and safeguarding freshwater resources.

Development of a deforestation footprint requires:

1. spatially explicit quantification of deforestation
2. a robust method for attributing deforestation to 'responsible' primary sectors (i.e. crops and livestock production, forestry, housing and infrastructure)
3. land flow accounting to track embedded deforestation through the supply chain

Deforestation data

Forest change dynamics are complex and vary from region to region. They include cycles of forest land reduction and growth induced by both human activities and natural causes. Moreover, countries or studies may apply different definitions of "forests" according to specific classification systems, assessment methods and monitoring frequencies.

Regularly provided and harmonized global data of the state of world's forests are available from the FAO (FAO 2010). FAO defines a forest or forest land as: "Land spanning more than 0.5 hectares with trees higher than 5 meters and a canopy cover of more than 10 percent, or trees able to reach these thresholds in situ. It does not include land that is predominantly under agricultural or urban land use."

Applying this definition entails that deforestation is defined as the process of converting forest land use (as defined above) to non-forest land uses. "Deforestation implies that forests are cleared by people and the land converted to another use, such as agriculture or infrastructure. Also natural disasters may destroy forests, and when the area is incapable of regenerating naturally and no efforts are made to replant, it too converts to other land."(FAO 2010)[20]

Note that FAO employs a land use concept rather than a pure land cover approach. The latter considers temporarily unstocked land as deforestation (e.g. in Hansen et al. 2010). In contrast the land-use approach considers areas of temporary forest loss (e.g. clear cut management, fire, or diseases), which are afforested or subject to natural regrowth as forest land.

The Forest Resource Assessment (FRA) reports for each country net changes in forest areas defined as follows: "The net change is the sum of all negative changes due to deforestation and natural disasters and all positive changes due to afforestation and natural expansion of forests." (FAO 2010)

Estimation of deforestation footprints requires data on gross deforestation rather than net deforestation. Gross deforestation or gross change in forest area is the sum of all forest area losses over a given time period and spatial entity (e.g. country).

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[19] http://www.consilium.europa.eu/ueDocs/cms_Data/docs/pressData/en/envir/104508.pdf

[20] It should be noted that forest degradation is not included in this definition. We recognize a significant impact of forest degradation on ecosystem services, climate change and biodiversity. Human consumption, especially of forestry products, may contribute to forest degradation. However data on forest degradation are even more challenging to obtain compared to forest loss data.

For the estimation of gross deforestation, reported FRA net forest area changes need to be supplemented with data on afforestation and/or natural regrowth. FRA 2010 reports regional afforestation rates for 2005 [21] and several countries report for individual periods.

A recent example of attributing reported deforestation during 1990 to 2008 to primary production and tracking embedded deforestation through the supply chain [22] can be found in Cuypers et al. (2013).

6 Quantification of selected indicators

Following the recommendations of the expert workshop (section 4.3) and building on available models and data we quantified the following indicators.

- First, we present two *system indicators*, one for cropland and one for grassland.
  System indicators adjust the area-based land footprints by applying weights for land quality to reflect spatial heterogeneities in natural conditions. Defined weights are applied for the normalization of land footprints across nations, thereby generating better comparable land footprints. Using land of higher qualities in terms of potential output per hectare implies access to more natural biophysical resources (e.g. water, solar energy, nutrients).
- Second, among the environmental impact indicators we select the *deforestation footprint*.
  In addition to its central message on the extents of deforestation embedded in human consumption it also provides a proxy for other important environmental impacts. They include changes in biodiversity, greenhouse gas emissions, soil organic matter content, and water regimes (both water quantity and quality).

We would like to underline that the selected indicators are a first step towards extending area-based land footprints with information on land quality and environmental impacts to achieve a better understanding of the interlinkages of national consumption patterns and sustainable land use domestically and abroad. Other priority indicators have been described above including irrigation water, energy use in agriculture. Quantification of these indicators require additional data compilation and are beyond the scope of this study.

6.1 System indicators

System indicators modify area-based footprints by land quality. Land quality and productivity depends on both biophysical conditions and agronomic management. While the former presents a natural constraint, the latter depends on socio-economic resources and development including human and technological capital, institutional support, access to agricultural input (fertilizer, pesticides, irrigation). Agricultural land may be highly productive due to agronomic management, e.g. large farm size, high application rates of fertilizer and pesticides, irrigation from unsustainable water resources. This may however result in detrimental environmental impacts including water pollution, loss of biodiversity, or decline in soil organic matter.

In accordance with the overall aim of this study to develop indicators towards a better characterization of consumption and sustainable land use, we aim for system indicators that avoid integration of potential negative environmental effects of agronomic land management practices. Therefore weights for cropland and grassland productivity should only reflect given biophysical 'natural' conditions.

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[21] Table 5.7 on p.96 in FAO, 2010

[22] see http://ec.europa.eu/environment/forests/impact_deforestation.htm

6.1.1 Grassland footprint weighted by biomass productivity

Grassland productivity varies widely across regions ranging from highly productive grasslands in Central Europe and South America to marginal conditions in semi-arid regions in Central Asia or the northern parts of the Sahel. FAOSTAT reports extents of 'permanent pastures and meadows' and livestock numbers for each country. However, distributions of ruminant livestock (e.g. cattle, sheep, goats) or the extents of grassland actually used for grazing is not reported. We therefore assume countries entire grassland extents are used for grazing ruminant livestock.

Spatially detailed grassland productivity data have been obtained from the Global Agro-Ecological Zones database (IIASA/FAO 2012) for the estimation of grassland productivity for each country globally. Biomass productivity represents long-term average climatic conditions (1960-2000). Average biomass productivity ('grassland yields') for each country was calculated from all 5 by 5 minutes grid cells (10 km at equator) with grassland land use (year 2000).

The wide range in global grassland productivity from over 8 t/ha in tropical countries to less than 1 t/ha in arid countries together with the assumption to attribute all grassland to ruminant livestock herds suggest to define more comparable grassland extents. This was achieved by normalization to a defined reference point of 2.06 tons (dry matter) biomass yield per hectare (Table 4). The selected reference point was chosen to represent mean biomass yield of global grassland areas. In this way for each country a reference grassland was calculated. In this way the relative share of each country in global grassland changes. Note that these shares do not depend with the chosen level of normalization. Globally we estimate the total annual biomass production from grassland amounting to some 7 billion tons (dry matter) biomass.

Table 4 presents for selected countries grassland yields as well as reported and reference grassland areas. For example, in Germany the average biomass productivity over all grassland land use gridcells amounts to 6.5 tons per hectare. As Germany's grassland yields in Germany are higher than the global mean, reported 5 Mha grassland area increases to 16 Mha_{eq} equivalent reference grassland area. China reports grassland extents of 400 Mha, i.e. 12 % of global total. Yet a significant amount is located in the semi-arid and arid Northwest where biomass productivity is marginal. Average biomass yields over China's entire grassland areas are only 1 ton/ha resulting in reference grassland extents of only 194 Mha_{eq} (6 % of global total). Similarly, reference grassland in Australia and Kazakhstan, countries with large grassland extents, is significantly lower compared to reported grassland extents.

In other words better land qualities with higher biomass potentials compared to the chosen reference land quality will increase the weighted grassland footprint (compared to an unweighted based on reported grassland) and vice versa in the case of lower land qualities. Land quality weighted footprints make footprints across countries more comparable and proxy human biomass utilization from grassland and potential impacts on natural resources.

Table 4: Average grassland yields, reported grassland areas and reference grassland areas normalized to 2.06 t/ha, 2000, selected countries

	Grassland yield[1] [tons/ha]	Reported grassland[2] [Mha]	Share in global	Reference grassland[3] [Mha equivalent]	Share in global
Germany	6.5	5	0.1 %	16	0.5%
France	6	10	0.3 %	29	0.9%
Russia	2	91	2.7%	88	2.6%

	Grassland yield[1] [tons/ha]	Reported grassland[2] [Mha]	Share in global	Reference grassland[3] [Mha equivalent]	Share in global
Kazakhstan	0.84	185	5.4%	75	2.2%
Brazil	5	196	5.8%	476	14.0%
Argentina	3	100	2.9%	146	4.3%
Uruguay	7.5	13	0.4%	49	1.4%
United States	3	236	6.9%	345	10.1%
Nigeria	2	39	1.1%	39	1.1%
Sudan	1.7	117	3.4%	97	2.8%
Saudi Arabia	0.02	170	5.0%	2	0.0%
China	1	400	11.8%	194	5.7%
Mongolia	0.67	129	3.8%	41	1.2%
Australia	1	408	12.0%	199	5.8%
Indonesia	9	11	0.3%	49	1.4%
WORLD		**3,400**	**100 %**	**3,400**	**100 %**

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

Large differences between reported and reference yields will result in significant differences between weighted and un-weighted grassland footprints. When ruminant livestock products from such countries enter trade (e.g. wool or sheep meat from Australia) differences in footprints are transmitted to other regions.

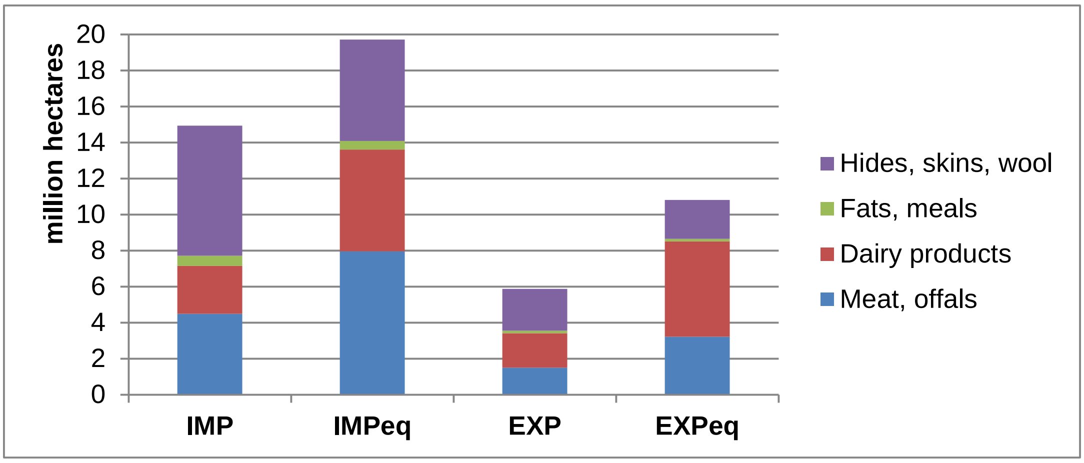
Below we describe the impact of normalization by land quality for Germany and the EU. We show the composition of the grassland footprint in 2010 when we measure grassland extents

1. as reported in FAOSTAT (in hectares) (Table 5,7) and
2. normalized to the global mean of about 2 t/ha biomass productivity (in hectares equivalent) (Table 6,8).

Germany

Germany's grassland extents attributed to domestic ruminant livestock production increases when the grassland footprint is normalized to 2 tons/ha. Germany imports significant amounts of grassland embedded in ruminant livestock commodities. Figure 3 highlights a strong effect of using a normalized hectare equivalents (IMPeq, EXPeq) as compared to actual grassland areas reported in FAOSTAT (IMP, EXP). Apparently significant imports of meat and hides, skins and wool and derived products (textiles) into Germany originate from countries with grassland areas above a productivity of 2 tons/ha. In this way grassland embedded in imports increases when measured in hectare equivalents.

Figure 3: Grassland embedded in trade, measured in hectares and normalized hectare equivalents, year 2010



Both Germany's domestic grassland and grassland embedded in trade increase because of the relatively low global mean productivity of 2 t/ha assumed for normalization (Table 5, 6). The grassland footprint measured in normalized hectares is 23.7 Mha equivalents compared to an unweighted grassland footprint of 13.7 Mha.

Table 5: Grassland footprint, Germany, 2010

1000 hectares	Domestic production	Net imports	Footprint[1] Total	SRR[2]	Footprint Food	Footprint Non-Food
Meat	1,228	2,993	4,221	29%	3,875	325
Dairy products	3,325	736	4,061	82%	3,492	336
Fats	36	419	454	8%	199	245
Hides, Skins, Wool	91	4,915	5,005	2%	n.a.	5,006
TOTAL	**4,680**	**9,063**	**13,741**	**34%**	**7,566**	**5,911**

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

Table 6: Grassland footprint normalized to 2 t/ha, Germany, 2010

1000 hectares equivalent	Domestic production	Net imports	Footprint[1] Total	SRR[2]	Footprint Food	Footprint Non-Food
Meat	3,878	4,743	8,622	45%	8,330	248
Dairy products	10,499	357	10,856	97%	9,642	571
Fats	114	347	461	25%	182	267
Hides, Skins, Wool	287	3,456	3,742	8%	n.a.	3,742
TOTAL	**14,778**	**8,903**	**23,681**	**62%**	**18,154**	**4,828**

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

Accordingly the grassland self-reliance ratio differs depending on the type of area measurements. By normalizing grassland to 2 t/ha biomass yields results in a grassland self-reliance of 62%, i.e. 38% of the footprint is from grassland outside Germany. In the absence of normalization the self-reliance ratio is only 34%, i.e. two thirds of the grassland footprint is sourced from abroad. The composition of the footprint in terms of food (meat, dairy) and non-food (hides, skins, wool) products 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 where the productivity is lower compared to Germany. In contrast the food-related grassland footprint is primarily sourced from domestic grassland, where biomass yields are higher compared to those of many importing regions of 'hides, skins and wool'.

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. In 1995 Germany's grassland footprint was 27.9 Mha and the weighted grassland footprint 13.5 Mha equivalents.

European Union

For the EU28 patterns in trade and composition of grassland footprints measured in reported extents (Table 7) as compared to normalized extents (Table 8) are similar as for Germany alone.

Table 7: Grassland footprint, EU28, 2010

1000 hectares	Domestic production	Net imports	Footprint[1] Total	SRR[2]	Footprint Food	Footprint Non-Food
Meat	23,608	19,780	43,541	54%	41,602	1,939
Dairy products	39,891	-392	39,405	101%	37,490	1,914
Fats	620	2,210	2,856	22%	1,397	1,459
Hides, Skins, Wool	3,767	28,513	32,506	12%	n.a.	32,488
TOTAL	**67,886**	**50,111**	**118,308**	**57%**	**80,489**	**37,800**

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

Table 8: Grassland footprint normalized to the global mean of 2 t/ha, EU28, 2010

1000 hectares equivalent	Domestic production	Net imports	Footprint[1] Total	SRR[2]	Footprint Food	Footprint Non-Food
Meat	53,636	33,036	86,988	62%	85,464	1,524
Dairy products	94,453	-4,013	90,225	105%	86,961	3,263
Fats	1,387	1,581	2,994	46%	1,463	1,531
Hides, Skins, Wool	8,505	16,939	25,753	33%	n.a.	25,729
TOTAL	**157,980**	**47,543**	**205,560**	**77%**	**173,888**	**32,047**

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

A major reason is again the strong influence of grassland embedded in imports of 'hides, skins, wool' sourced from countries with yields below the global average of 2 t/ha (e.g. China, Australia) used for normalization. On average grassland productivity in the EU28 is above 2 t/ha. This results in a higher share of EU grassland in global grassland (4.6 %) when measured in normalized grassland equivalents (158 Mha_{eq}) compared to reported grassland extents (68 Mha or 2 % in global total). The same applies for net imports and the EU grassland footprint extents, which are 167 Mha_{eq} (4.9 % in global total) and 118 Mha (3.5 % in global total) when grassland is normalized or not.

6.1.2 Cropland footprint weighted by land quality

Cropland is concentrated on the World's most fertile regions, nevertheless land varies considerably with environmental conditions and management applied. For a better comparison of footprints across nations and a better understanding of the impacts of foot prints we have scaled area based footprints of cropland according to land quality. We compare in the following (scaled) land quality weighted ("Cropland-LQw") and (unscaled) crop land extent ("Cropland") footprints.

In deriving land quality we consider irrigated and rain-fed crop production separately. Globally, as of 2010 one fifth of the about 1500 Mha global cropland (321 Mha) are equipped for irrigation (FAOSTAT). In semi-arid and arid climates economic crop cultivation is, by necessity foremost, relying on irrigation (e.g. Egypt, Israel, Pakistan, Northern India, Northern China). Certain commodities, like wetland rice, are cultivated almost exclusively in irrigated land. In Egypt or Pakistan almost all cropland is equipped for irrigation. India and China have large tracks of irrigated cropland amounting to 67 Mha (39% of total cropland in India) and 66 Mha (54% of total cropland in China) respectively. Despite the crucial and increasing role of irrigation in global crop production it is important to note the dependence on water-management and availability of renewable water resources. Due to increasing surface and groundwater scarcity, irrigated crop production has become unsustainable in many parts of the world.

For these reasons, and according to our quest to develop footprint indicators in the context of sustainable land use, we account for rain-fed and irrigated land separately in the estimation of quality of cropland. Land quality weighted cropland we use here as a proxy for the human exploitation of biophysical land and water resources. The spatial system boundary of this estimate is current land use for crop cultivation. The higher the land quality weighted cropland extents the higher the exploitation of available land and water resources. To a lesser extent land quality weighted cropland may approximate impacts on biodiversity as higher Cropland-LQw occurs in tropical regions of high biodiversity.

Technically land quality is calculated as the basis of attainable terrain and soil constrained net primary production (NPP) separately for both rain-fed and irrigated cropland. GAEZ databases (IIASA/FAO 2012) provide (year 2010) land use and quality in each 5 arc-minute grid-cell[23] across the world. GAEZv.3 provides downscaled land use statistics for seven major land use/cover categories including rain-fed and irrigated cropland. This land quality is defined as the biophysical potential of location specific land resources assuming agro-climatic conditions (average climate 1981-2010), soil properties of current (year 2000) rain-fed and irrigated cropland, terrain (e.g. slope), and presence of irrigation infrastructure. Note that we aim for an index of biophysical potentials and therefore do not consider productivity due to agricultural inputs (fertilizer, pesticides) and crop management (seed quality). For each country we finally calculate average land quality over all rain-fed and irrigated cropland grid-cells.

The reference point for normalization has been defined as the global mean productivity of current rain-fed and irrigated cropland. China emerges as a country representing the global mean productivi-

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[23] A 5 arc-minute grid-cell is highest around the equator (about 8 km) and decrease gradually to 5 km near the poles.

ty of about 20 tons DM biomass per hectare (or about 10 tons DM cereal equivalent). In this way we can transform statistically reported cropland extents to cropland extents weighted by land quality (Table 9).

Table 9: Cropland and land quality weights, 2010, selected countries

	Cropland [Mha]	Irrigation Share	Land quality weight[1]	Cropland-LQw[2] [Mha equivalent]
Germany	12	5%	0.827	10
EU28	121		0.835	101
Russia	122	4%	0.681	83
Canada	48	2%	0.693	33
USA	158	12%	1.096	173
Australia	46	6%	0.648	30
India	169	39%	1.306	221
China	122	55%	1.016	124
Indonesia	45	15%	1.203	54
Brazil	78	7%	1.066	83
Argentina	37	6%	1.113	42
Egypt	3.7	99.7%	1.673	6
World	**1,516**	**21%**	**1**	**1,516**

1: Land quality calculations are derived from the GAEZ databases. We normalize to the mean of land quality across current (year 2010) global rain-fed and irrigated cropland; **2** Cropland weighted by land quality = Cropland * Land quality weight

In general, irrigated cropland and rain-fed cropland in sub-humid tropical climates have higher land productivities as compared to cropland in temperate seasonal climates. Countries with a high share of irrigated cropland (e.g. Egypt, Israel, Northern India, Northern China) or countries located in sub-tropical or tropical climates may have land quality weights above 1, i.e. land quality weighted cropland extents exceeds actual cropland extents. For example, India's share in global cropland is 11.1 % compared to 14.6 % for land quality weighted cropland. Land quality weights below 1 are found in countries with temperate seasonal climates (Central Europe, Russia) and of high latitudes (Canada). For instance, the EU28's 121 Mha cropland (7.96 % of global cropland) equates to 99 Mha land quality weighted cropland (6.61 % of global).

Irrigation and climatic conditions are also reflected in crop composition and cropping patterns across cropland areas. For example, some 8.9 % of global cropland (135 Mha) is cultivated for the production of rice, mainly in Asia with 86% of global area almost exclusively under irrigated rice. When converted into land quality weighted cropland this share increases to 10.2% or 156 Mha_{eq}. Similarly, land quality weighted cropland for stimulants (coffee, cacao, tea) or natural rubber, both cultivated in tropical countries, often increases when expressed as land quality equivalents.

Wheat and fodder crops are cultivated primarily in temperate seasonal climate zones, where land quality weights are below our reference point of 20 tons biomass/hectare. Therefore "Cropland-LQw" is often lower compared to "Cropland". For wheat and fodder crops the share in global cropland is 16.3% and 12.5% respectively, compared to 14.6% and 10.9% for "Cropland-LQw".

As for unweighted cropland ("FP-Cropland"), the Cropland-LQw has been tracked along supply chains to final consumption for the calculation of cropland footprints weighted by land quality (FP-Cropland-LQw). Table 10 compares the composition of the global footprint in terms of actual hectares with land quality weighted extents. At the global level the share of livestock based food decreases when cropland is measured in land quality weighted extents. This implies that cropland embedded in livestock products is mainly coming from relatively lower land quality resources. In contrast the relative share of food and non-food consumption is higher when measured in land quality weighted extents.

The amount of crop and livestock products entering trade comprises 32.5% of global cropland when cropland is measured in land quality weighted equivalents, only somewhat lower than the 33.8% for (unweighted) cropland extents.

Table 10: Global cropland footprints, Comparison of reported extents and extents weighted by land quality, 2010

	FP-cropland[1] [Mha]	Share	FP-Cropland-LQw[2] [Mha_{equ}]	Share
Food, crops	742	48.9 %	769	50.7 %
Food, livestock	477	31.5 %	446	29.4 %
Non-food	178	11.8 %	185	12.2 %
Seed, On-farm waste	119	7.8 %	116	7.7 %
TOTAL	1516	100 %	1516	100 %

1 Cropland footprint measured in reported hectares; **2** Land quality weighted cropland footprint measured in hectare equivalents (see text).

Germany

Overall Germany's land quality weighted cropland area footprint results in a smaller share (1.36 %) of global cropland resources compared to an unweighted cropland footprint (1.48 %). This is caused by Germany's domestic crop cultivation on cropland in temperate seasonal climate. Net imports on aggregate remain fairly similar for land quality weighted and unscaled footprints, implying a lower share of the domestic origin (Table 11). In other words, when land quality is taken into account, the fraction of the footprint that comes from cropland outside German territory is higher (51.4 %) compared to the unweighted result (45.9 %). Both land quality weighted and unweighted footprints exceed the 1.2 % share of Germany's population in global population.

Although net imports are about equal for both types of footprint calculations, especially imports differ significantly at commodity level. Stimulants, vegetable oils, oil cakes, rubber, industrial fibre crops, and alcohol show relatively higher shares in total imports in terms of weighted cropland. The share of other imported commodities decreases.

Table 11: Cropland footprint, area-based and weighted by land quality, Germany, 2010

	Cropland [1000 ha]	Cropland-LQw [1000 ha_{equ}]
Domestic crop cultivation	12,088	9,998
Net imports	10,607	10,851

	Cropland [1000 ha]	Cropland-LQw [1000 ha_{equ}]
From stock	-336	-269
Cropland footprint[1]	22,359	20,580
Domestic origin of footprint[2]	54.1 %	48.6 %
Share of footprint in global cropland	1.48 %	1.36 %

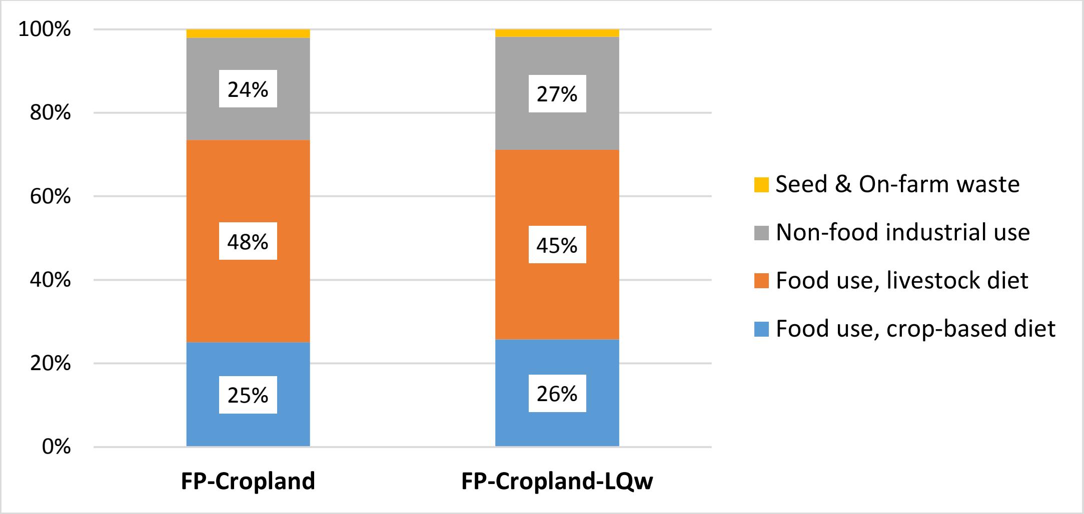
1 Cropland footprint = Domestic crop cultivation + Net Imports corrected for stock changes; **2** Share of footprint sourced from crops cultivated on domestic cropland

Scaling cropland extents by land quality reduces the share of the livestock-based food of the cropland footprint in favour of the crop-based food diet combined with the non-food sector (Figure 4). Footprints at the commodity level reveal the importance of stimulants (coffee, cacao, tea) for the relative increase of the fraction of the footprint related to crop-based diets. While stimulants account for 6.25 % in unadjusted cropland extents, this share increases to 8.08 % in scaled footprints.

Other commodities whose share in scaled cropland footprints is larger compared to unscaled cropland footprints include fruits/vegetables/spices, rice, primary oil crops and vegetable oils. Most of these commodities are cultivated in tropical/sub-tropical climates and/or are irrigated.

The relative share of the remaining commodities in the total footprint, in particular livestock products, is smaller for scaled cropland compared to unscaled cropland. This is due to the production of feed crops produced in countries with relatively lower land qualities. The majority of feed crops embedded in Germany's food livestock consumption originates from Germany (61 %) and other countries of the European Union (23 %) (see Table 8 in Fischer et al 2016).

Figure 4: Composition of the Cropland Footprint, unscaled (FP-Cropland) and weighted with land quality (FP-Cropland-LQw), Germany, 2010



The relative importance of commodities cultivated in tropical climates and/or irrigated commodities are reflected in the global origin of the food-related cropland footprint. The combined food-related footprint in Latin America, Africa and Asia amounts to 11.8 % for unadjusted cropland, compared to 15.1 % for adjusted cropland (Table 12).

Table 12: Origin of Germany's food related footprints, 2010

	Germany	Other EU28	Latin America	Africa	Asia	Rest of World
FP-Cropland	61.2 %	23.2 %	4.8 %	3.1 %	3.9 %	3.8 %
FP-Cropland-LQw	58.9 %	22.4 %	6.3 %	3.7 %	5.1 %	3.6 %

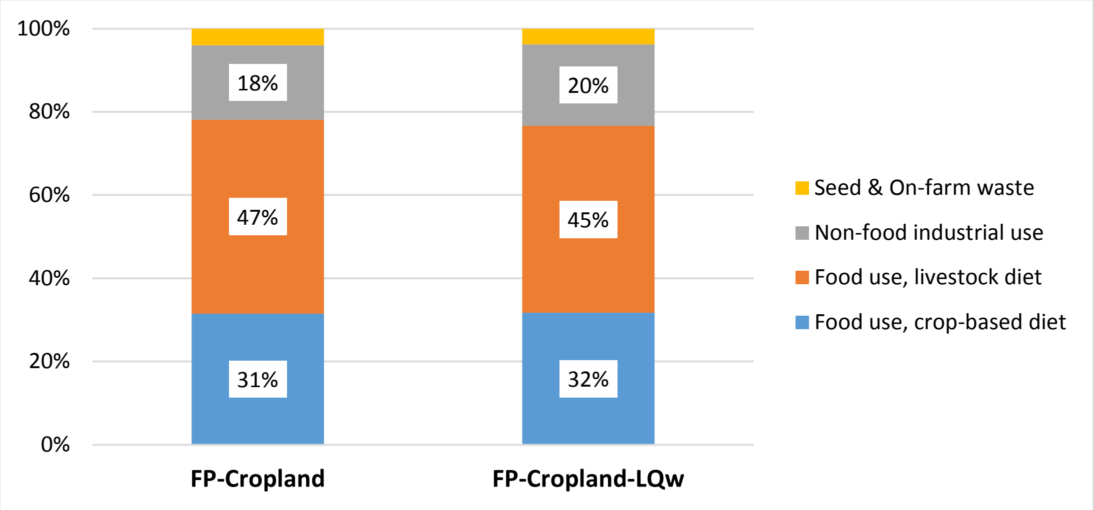
European Union

The European Union as a whole shows similar tendencies as Germany when comparing footprints for unscaled and land quality weighted cropland extents. The proportion of the EU28 cropland footprint in global cropland is somewhat smaller (9.3 %) for land quality weighted cropland than for unscaled cropland (10.4 %). However, both are larger than the share of the EU28 in global population (7.3 %). More than two thirds (71 %) of the land quality weighted cropland footprint (141 Mha equivalent) originates from food, feed and fibre crops cultivated in the EU28 (Table 13). The remaining 29 % relies on cropland outside the EU28. For unscaled cropland the external cropland share is only 23 % indicating that imports tend to be sourced from countries where the productive capacity of cultivated land on average is rated higher than for the EU.

It is notable that cropland self-reliance significantly differs between Eastern and Western Europe. One third of EU cropland is located in Eastern European countries (Poland, Czech Republic, Slovakia, Hungary, Bulgaria, Romania, Slovenia) home to one fifth (21 %) of the EU population. Eastern Europe is more than self-reliant, i.e. extents of cropland embedded in consumption is some 6-9 % lower (depending on whether measured in reported or land quality weighted areas) than cropland extents. Eastern Europe is thus a net exporter of cropland. Main exported commodities include cereals, oil crops, and meat and dairy products.

Due to large differences in the import and export share of different commodity groups, the composition of the EU28 cropland footprint varies somewhat (Figure 5) depending on whether unweighted or quality weighted extents are used in the calculation. When quality-weighting is applied, the cropland footprint share related to livestock products decreases from 47 % to 45 % whereas the percentages contributed by crop-based food use and industrial non-food uses of cropland increase.

Figure 5: Composition of cropland footprint (FP-Cropland) and land quality weighted cropland footprint (FP-LQw), EU28, 2010



Expressing the cropland footprint of EU28 in quality adjusted area extents results in about 141 Mha or 9.3 % of global cropland, less than the unweighted footprint of 157 Mha or 10.4 % of global cropland (Table 13). This indicates that on average European cropland is given a lower weight than the cropland of countries from where imports are obtained. This result is mainly due to climatic factors and Europe's geographic position, which allow often only one crop per year for European cropland whereas two or even three crops can be cultivated in countries of the tropics or sub-tropics, rendering cropland in these countries potentially more productive then in the temperate zone. For the same reason cropland self-reliance of the EU28 falls from 77 % (unweighted case) to 71 % when applying quality-weighting to cropland extents.

Table 13: Cropland footprint, area-based and weighted by land quality, EU28, 2010

	Cropland [Mha]	Cropland-LQw [Mha_{equ}]
Domestic crop cultivation	120,698	100,538
Net imports	35,182	39,266
From stock	1,554	1,437
Cropland footprint[1]	157,435	141,241
Domestic origin of footprint[2]	77 %	71 %
Share of footprint in global cropland	10.4 %	9.3 %

1 Cropland footprint = Domestic crop cultivation + Net Imports corrected for stock changes; **2** Share of footprint sourced from crops cultivated on domestic cropland

6.2 Deforestation footprint

6.2.1 Methodology overview

As described above (section 5.4) estimation of deforestation footprints requires

1. a 'land use' definition of forests (i.e. management cycles in forest management with temporary fallow periods are not regarded as deforestation), and
2. data on gross deforestation rather than net deforestation. *Gross deforestation* or gross change in forest area is the sum of all forest area losses over a given time period and spatial entity (e.g. country). Net deforestation in addition accounts for afforestation and natural regrowth.

In summary, gross deforestation includes all land where a 'forest' land use was converted to other land uses, e.g. agricultural land, built-up areas, or any other natural land uses. We apply gross deforestation for the calculation of consumption based deforestation footprints. For better legibility we henceforth speak of 'deforestation' instead of using the term 'gross deforestation'.

Before tracking embodied deforestation along supply chains, a robust method is required to attribute deforestation to 'responsible' primary sectors, i.e. the crops and livestock products produced from deforested land.

As deforestation data is not reported by 'responsible' sector, further assumptions and methodologies are required for attributing to main drivers of deforestation including relevant economic activities and natural causes:

1. Cropland: Cultivated land expansion and related crop production increases and disaggregating crop production for specific crops
2. Livestock: Pasture expansion and ruminant livestock production increases
3. Built-up land: Expansion of rural settlement, urban areas and infrastructure
4. Round wood: Industrial round wood extraction (logging followed by agricultural expansion)
5. Natural hazards: fire mainly
6. Unexplained: Any 'unexplained[24]' deforestation, i.e. residual not explained by any of the other causes

Annex 4 describes the applied IIASA land use change model and data to achieve the attribution to main causes and sectors including the allocation of deforestation for agricultural expansion to specific primary crops and livestock animals.

A key assumption has been to account for direct and indirect (distant) land use change effects. For example cropland expansion for particular crops (e.g. soybean) may be attributed to deforestation indirectly by occurring on land outside the deforested areas while expansion of pastures or other crops is the direct agent of deforestation. Increases in harvested areas of individual crops or increases in pasture land were attributed to 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 we focus on three periods of deforestation, 1995-2000, 2000-2005, and 2005-2010.

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[24] When deforestation cannot be explained by either of the factors (agriculture, logging, build-up area increases or natural hazards), the remainder is termed 'Unexplained'. This applies to about one fifth of global reported deforestation. Reasons for 'unexplained' deforestation may be manifold including illegal logging, the result of long-term degradation effects due to many informal practices in forests, or erroneous deforestation figures (over-reporting) and agricultural area data on national level (under-reporting).

Extents of deforestation embodied in individual primary crops and livestock products were finally tracked through the supply chain to final consumption using the hybrid methodology for land footprint calculations applied in this study (Fischer et al. 2016).

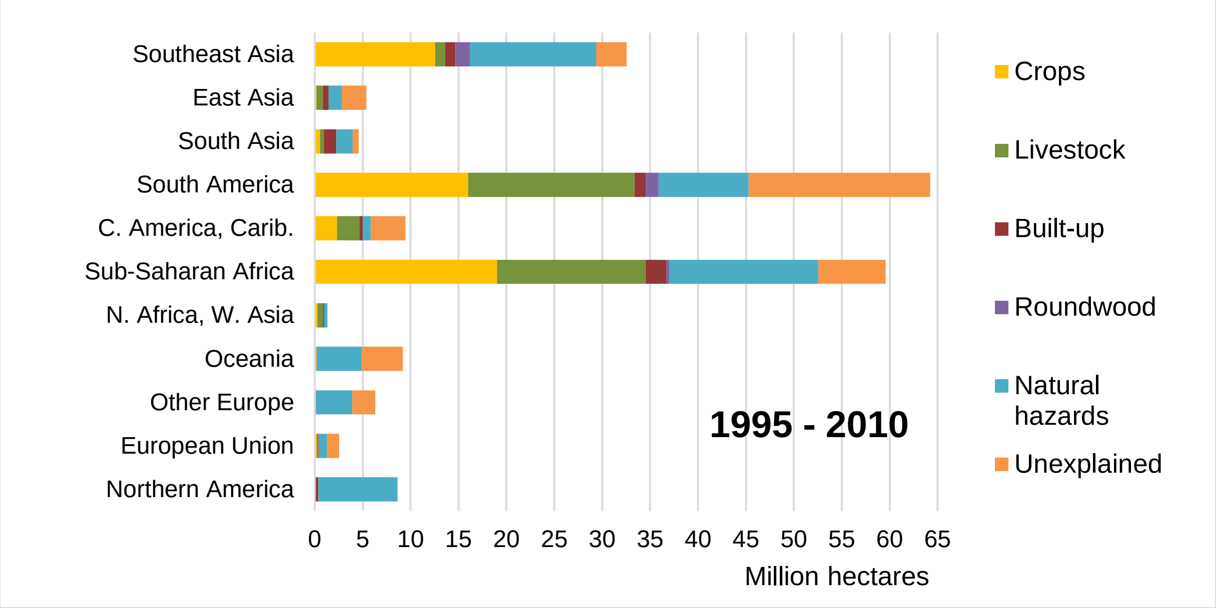
Attribution of deforestation to main sectors

Global deforestation between 1995 and 2010 was 204 Mha with the trend decreasing (Table 14). Some 44% can be attributed to the agricultural sector comprising of 51 Mha and 38 Mha deforestation due to the expansion of crop and ruminant livestock production respectively. Figure 6 highlights the regional distribution of deforestation and associated causes. Over the 15 year period deforestation was concentrated in South America (32% of total), Sub-Saharan Africa (29%) and Southeast Asia (16%). In all three regions expanding crop production was a major agent of deforestation. In South America and Sub-Saharan Africa also pasture expansion for ruminant livestock production caused deforestation.

Table 14: Global extents of deforestation attributed to main sectors, 1995 to 2010

1000 hectares	Crops	Livestock	Built-up	Roundwood	Natural hazards	Unexplained	TOTAL
1995-2000	13,732	14,949	2,454	837	23,994	16,523	72,489
2000-2005	20,661	14,211	2,433	1,316	19,949	8,132	66,702
2005-2010	16,873	8,955	2,412	1,020	16,046	19,235	64,541
TOTAL	51,266	38,115	7,299	3,173	59,989	43,890	203,732

Figure 6: Regional extents of deforestation attributed to main sectors, 1995 to 2010



6.2.2 Deforestation footprints

Deforestation attributed to the agricultural sector (Table 14) has been tracked from the deforestation content of the primary commodity in a specific country (e.g. soybean in Brazil, cacao in Sierra Leone, oil palm in Indonesia) through global supply chains to final consumption using the hybrid methodology for land footprint accounting applied in this study (Fischer et al. 2016).

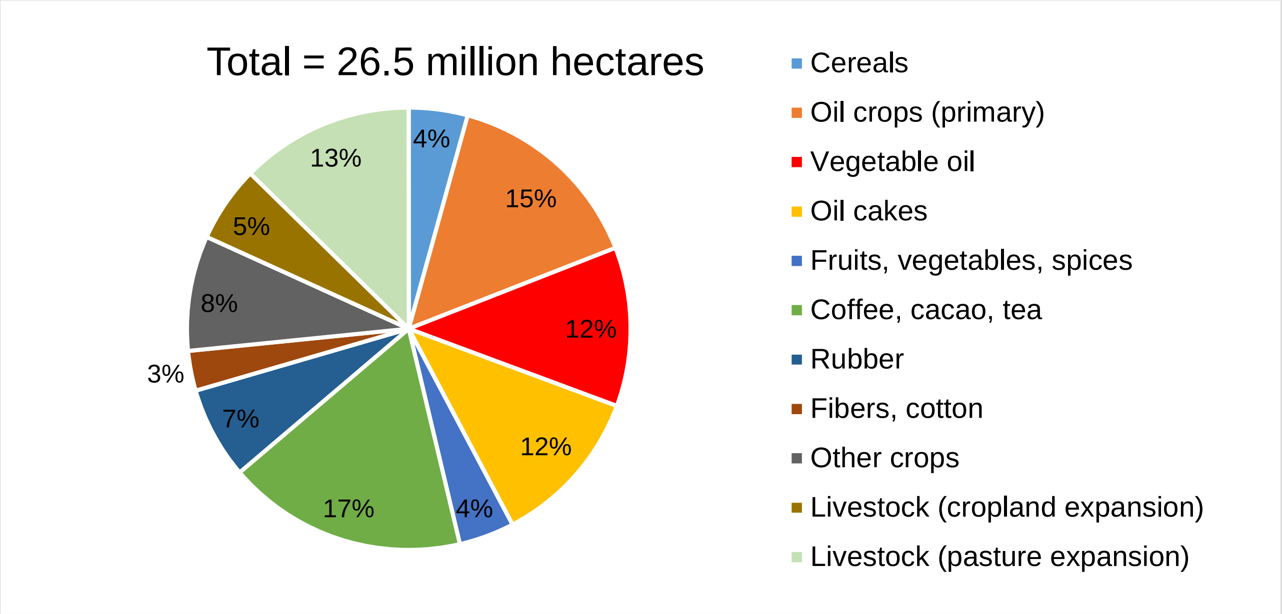
Deforestation embodied in trade and global deforestation footprints

Between 1995 and 2010, some 23.2 Mha or almost half (45%) of deforestation extents attributed to cropland expansion for food and feed crop production enter trade. In addition 3.3 Mha or 9% of deforestation attributed to pasture expansion for ruminant livestock production enters trade. Therefore a total of 26.5 Mha of deforestation embodied in agricultural commodities is translocated from one country to another.

Figure 7 highlights the agents of deforestation entering trade by major commodity group. The oil crop sector including primary oil crops, vegetable oil and oil cakes has taken a central role in transferring deforestation between countries with as much as 10 Mha of deforestation embodied in traded commodities. South America is the main exported region of over 7 Mha deforestation embodied in oil crop products, of which Brazil alone exported 3.9 Mha. Vegetable oil and embodied deforestation is imported throughout the world. In the case of primary oil crops and oil cakes the European Union takes a prominent role in importing embodied deforestation (almost 4 Mha for EU demand).

Other important crop commodities include coffee, cacao, tea (4.6 Mha embodied deforestation), as well as a variety of industrial crops (natural rubber, fibres, cotton; 2.6 Mha). Livestock products entering trade and contributing to deforestation are due to both feed crops cultivated on expanding cropland and ruminant livestock products grazing on expanding pastures and cause in total some 4.8 Mha of deforestation.

Figure 7: Cumulative deforestation 1995 to 2010 entering trade, by major commodity group



At the global level half of the deforestation footprint (44 Mha) is due to food consumption of livestock products. This results primarily from pasture expansion for ruminant livestock (e.g. cattle) production (34 Mha), followed by expansion of cropland for increasing feed crop production (10 Mha) (Table 15). One third (28.6 Mha) of global deforestation was attributed to the consumption of crop-based food. This includes food from cereals (9.4 Mha), fruits/vegetables/spices (4.7 Mha), vegetable oils (4.1 Mha), and coffee/cacao/tea (3.2 Mha).

Some 12% (10.6 Mha) is for the consumption of non-food commodities produced from agricultural crops and livestock products causing deforestation. The remaining 5% (4.7 Mha) is attributed to land equivalents required for seed production and on-farm waste.

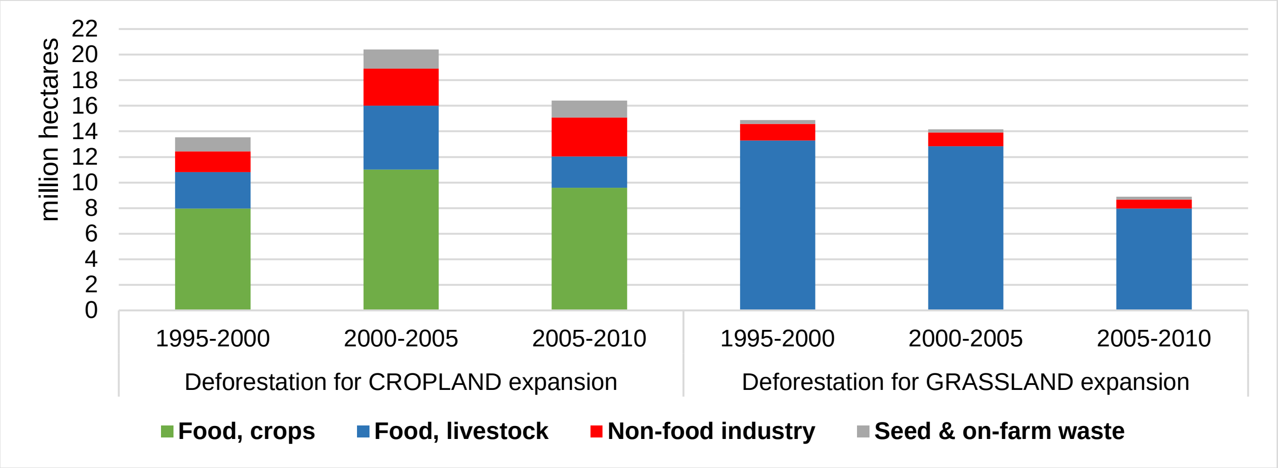
Table 15: Global deforestation footprint, cumulative 1995 to 2010

1000 hectares	FOOD, crops	Food, livestock	Non-food industry	Seed / Waste	TOTAL	
Deforestation attributed to						
Cropland expansion for food and feed crop production	28,594	10,283	7,537	3,940	50,335	57 %
Pasture expansion for ruminant livestock production	n.a.	34,086	3,100	744	37,930	43 %
TOTAL	28,594	44,370	10,636	4,684	88,285	
	32 %	50 %	12 %	5 %		

n.a. not applicable

Figure 8 highlights the trend in the global deforestation footprint separate for deforestation from cropland and grassland expansion. The deforestation footprint peaked between 2000 and 2005 (35 Mha) mainly due to cropland expansion and was lowest (25 Mha) in the latter period 2005 to 2010.

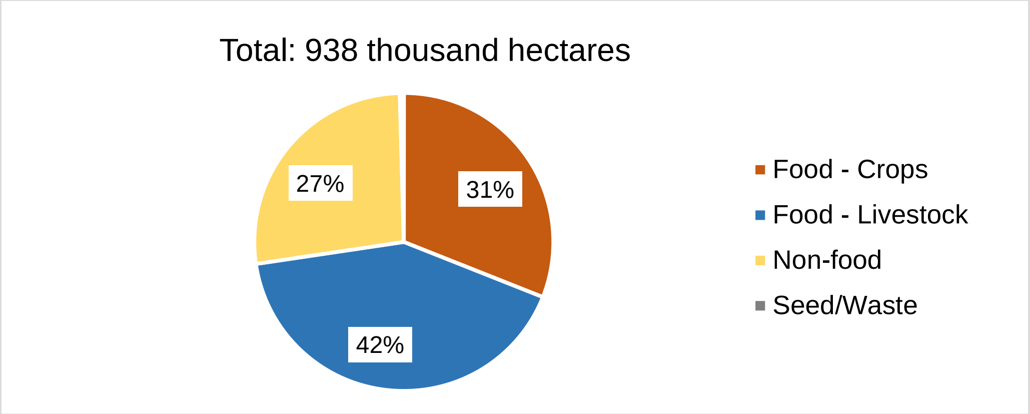
Figure 8: Global deforestation footprint 1995 to 2010, by consumption item



Germany

Between 1995 and 2010 we estimate the contribution of consumers in Germany to global deforestation amounting to 938 thousand hectares. About three fourth of the deforestation footprint are due to food consumption, mainly for livestock products, and one fourth due to non-food consumption for diverse industrial products (Figure 9).

Figure 9: Deforestation footprint of Germany, 1995-2010 (cumulative)



The vast majority (90%) of deforestation embedded in Germany's consumption results from cropland expansion for food and feed crop production (840 thousand hectares), the remaining 10% from pasture expansion and ruminant livestock production (98 thousand hectares). Important commodities contributing to deforestation for food include stimulants (coffee, cacao, tea; 26% of total cumulative food deforestation), meat (25% pigs & poultry, 7% cattle), dairy products (15%), vegetable oil (13%), and fruits/vegetables/spices (6%).

The main non-food products consumed in Germany and causing deforestation elsewhere include commodities produced from vegetable oils (29%), natural rubber (24%), alcohol (16%), cotton and fibres (11%), tobacco (4%), and diverse livestock based non-food (e.g. hides & skins, dairy products 8%).

Following global trends almost half (46%) of deforestation occurred between 2000 and 2005 and another 30% between 1995 and 2000. After 2005 deforestation declined resulting in a lower deforestation footprint (Table 16). The composition of the deforestation footprint changed over time towards a higher impact of the non-food industrial sector. While during 1995 and 2000 only 21% of deforestation is due to the non-food consumption, this share increased to 45% in the last period 2005-2010.

Table 16: Composition and evolution of deforestation footprint, Germany, 1995 to 2010

[1000 ha]	FOOD	of which Crops	of whichLivestock	NON-FOOD	TOTAL[1]	per capita [square meters]
1995-2000	227	109	118	61	289	35
2000-2005	334	115	220	93	429	51
2005-2010	121	68	53	99	221	27
TOTAL	682	291	391	253	938	113[2]

1 includes land equivalents for seed production and on-farm waste; 2 based on 83 million average population between 1995 and 2010

As expected all deforestation in German consumption occurs outside Germany's territory. Some 3.6% of commodities[25] with embedded deforestation entering trade or 1.1% of all deforestation attributed to the agricultural sector can be attributed to German consumption. Putting this into perspective Germany's share in global population was 1.45% in 1995 and decreased to 1.23% in 2010.

Per capita the deforestation footprint of every German citizen amounts to 113 m² cumulatively over the 15 year period or an average annual rate of 7.5 m² per capita. This compares to a global average per capita deforestation[26] of around 140 m² over the entire period (9.3 m² per capita annually). As outlined above some 50% of cropland expansion and 80% of pasture expansion resulting directly or indirectly in deforestation are embedded in commodities consumed in the country of deforestation.

Below we discuss the impact oriented deforestation footprint in relation to Germany's land footprint. In 2010 Germany's area-based cropland footprint was 22.3 Mha. The origin of cropland where food and feed crops were cultivated for German consumption comprise of 49% domestic cropland, 21% EU28 countries and 30% or 6.6 Mha from diverse other countries of the world (see Table 8 and 9 Fischer et al. 2016). Between 1995 and 2010 the cumulative deforestation for cropland expansion only (i.e. excluding pasture) was 840 thousand hectares. Thus the average annual deforestation impact of German consumers was 56 thousand hectares. This equals 0.85% of the imported land equivalent from Non-EU countries.

In other words: Every year about 1% of cropland embedded in crops sourced from non-EU countries caused deforestation. The oil crop sector, mainly in the form of oil cakes for feed and vegetable oil for food and non-food commodities, plays a prominent role in transmitting deforestation to Germany. Other commodities transmitting deforestation include coffee, cacao, tea and fruits. Note that German consumption related deforestation occurs to the largest extent in tropical countries with impacts on biodiversity loss and increased greenhouse gas emissions.

European Union

The cumulative deforestation footprint of the EU28 over the period 1995-2010 was 6.2 Mha. Half of this amount results from the consumption of livestock food, about one quarter from crop-based food and one fifth from non-food products (Figure 10). To put this into perspective 7% of deforestation attributed globally to the agricultural sector between 1995 and 2010 results from consumption of EU28 citizens. The majority (84%) of the EU28 deforestation footprint is embedded in consumption of expanding crops causing directly or indirectly deforestation. The remainder is associated with ruminant livestock consumption from increasing livestock herds that directly or indirectly resulted in grassland expansion into forests.

Almost half of the deforestation footprint was due to consumption between 2000 and 2005. The share of non-food was highest in the last period 2005-2010 amounting to 35%. Cumulatively over the 15 year period, consumption of every EU citizen resulted on average in a deforestation of 125 square meters (Table 17).

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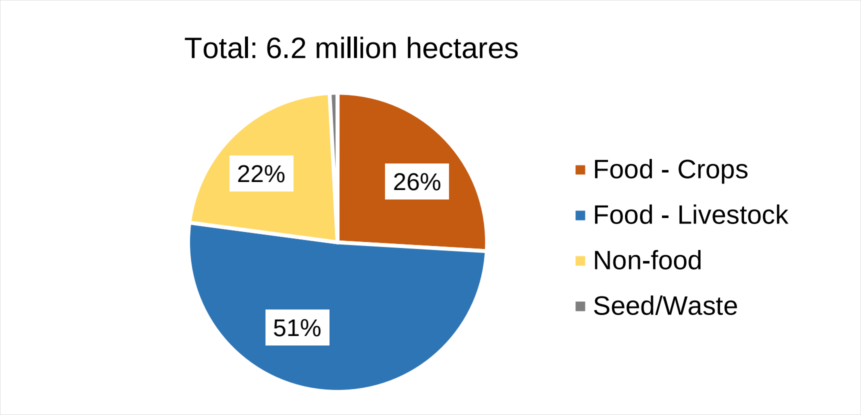
[25] German consumption contributed to 840 thousand hectares deforestation caused by the imports of crops from cropland expanding into forests. This represents a share of 3.6 % of the total 23,202 thousand hectares deforestation for cropland expansion entering trade.

[26] Number based on the average global population between 1995 (5741 million) and 2010 (6753 million).

Figure 10. Deforestation footprint of the EU28, 1995-2010 (cumulative)



Some 10 % (or 5.2 Mha) of global food and feed crops attributed to expanding cropland causing deforestation between 1995 and 2010 are embedded in EU consumption, a fraction higher than the EU28 share in global population, which was 8.4% in 1995 down to 7.3% in 2010. Important commodities that have contributed to this disproportionally high share in global deforestation include: Food use livestock products[27] (2.4 Mha); Coffee/Cacao/Tea (0.86 Mha); Food use of vegetable oil (0.4 Mha); Rubber and other industrial crops (0.4 Mha); Non-food use of vegetable oil (0.3 Mha); Fruits/vegetables/spices (0.2 Mha); Non-food use of alcohol & tobacco (0.2 Mha).

Table 17: Composition and evolution of deforestation footprint, EU28, 1995 to 2010

[1000 ha]	FOOD	of which Crops	of which Livestock	NON-FOOD	Total[1]	Total per capita [square meters]
1995-2000	1525	538	987	341	1884	39
2000-2005	2373	607	1766	546	2943	59
2005-2010	884	463	421	479	1375	27
TOTAL	4782	1609	3173	1367	6203	125[2]

1 includes land equivalents for seed production and on-farm waste; 2 based on 497 million population, i.e. average between 1995 and 2010.

7 Conclusions

Increasing populations, rapid income growth in emerging economies, and existing resource intensive consumption patterns in developed countries are placing unprecedented demand on land, water and ecosystems. This includes agro-inputs such as crop resources, agro-chemicals, nutrients and energy resources, as well as natural ecosystems. At the same time globalization and complex supply chains render it increasingly difficult for consumers to fully understand the resource and environmental impacts of their consumption decision. Yet, such understanding and quantification is important. For example, direct and indirect impacts of the usage of vegetable oil for food, biofuels and other oleochemicals or of soybean cake for livestock feed have received significant attention in the context of tropical deforestation (Rudel et al. 2009, Searchinger et al. 2008, EC 2013).

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[27] Embedded deforestation is to the largest extent transmitted via oilseed cake protein feed used for raising domestic livestock.

Land footprints provide a metric for the characterization of land use from a consumer perspective, i.e. a consumption-based indicator. The quantification of area-based land footprints, i.e. measured in actual hectares of land used (Fischer et al. 2016), was a first step towards consumption based accounts and indicators. In a second step, this study has extended land footprints towards quality and impact oriented land indicators for providing more specific information on sustainable land use and management linked to consumption patterns.

The quest for sustainability in land use/management and land use change has a broad scope and encompasses interlinkages with biodiversity loss, hydrology, climate change, soil conservation as well as cuts across several socio-economic dimensions (e.g. land governance and land tenure, achieving global food security, preservation of the recreation and cultural value of land). Against this broad background, we address in this scoping study the challenge of defining useful and practical land indicators from both a sustainable land use and a consumption-based perspective.

Towards this goal we've first summarized available indicators and have structured them in terms of their relevance for indicating environmental impacts, land intensity and land use change. The compiled indicators were scrutinized for their ability to approximate the status and sustainability of environmental goods (biodiversity, soil, water, climate), their ability to describe impacts on provisioning services (i.e. food and wood production), and their usefulness for capturing resilience of the respective land use system. Also, the identified indicators were reviewed for the potential linkages to primary production activities and the consumption perspective of land footprint accounting. Two main strains for analysis were identified. Area-based land footprints were extended to account for quality and effectiveness of the use of embedded land resources on the one hand, and to indicate important environmental (and social) impacts and pressures due to the involved land use systems on the other hand.

Like for simple area-based land footprints, the extended footprint analysis entails attributing land quality or environmental characteristics captured by the chosen indicator to land use and primary production globally and tracking them along the global supply chain to final consumption. While tracking can be achieved by using the hybrid land footprint methodology developed in this study, attribution of impacts to primary production activities requires solving data-related as well as conceptual challenges. Examples of data limitations include the lack of comprehensive multi-period global databases for soil degradation (e.g. soil erosion, change in soil organic matter), status and loss of biodiversity, water quality, or wetland loss.

Conceptual (and data) challenges occur when it is difficult or ambiguous to attribute to individual primary crops (which are then tracked along supply chains) the impacts like soil fertility loss, soil erosion, deforestation, or water pollution. Unlike area-based land footprints, where available data allow annual reporting, land quality and environmental impact extended land footprints are limited by data availability and can often only be estimated for selected time periods or years. For example, global deforestation data are estimated and published at an interval of five to ten years. Data on water withdrawal for irrigation, source of irrigation water, or on groundwater recharge is hardly available for more than individual years. Data limitations and conceptual challenges for connecting environmental impacts with different primary production activities suggest a step-wise approach for the analysis of consumption related impacts in the context of sustainable land use.

First, consumption patterns are analysed using area-based land footprints covering the entire economy of a nation/region, with a high level of commodity detail and using annual time steps (see Fischer et al., 2016). Next, area-based footprints are further qualified by taking into account and differentiating the productive capacity of used land resources. This allows for a context sensitive and therefore more meaningful comparison of footprints across nations, differences of use of the production capacity and biomass associated appropriation of croplands. Finally, environmental impacts are quantified to the extent possible. Quantification requires context specific expertise and resources for modelling. A challenge for both, the assessment of land quality and environmental impacts, is related to data limitations for capturing a temporal dimension of an impact (e.g. loss of soil carbon over time).

Possible indicators were presented, discussed and agreed on in an international expert workshop (see section 4.3) which resulted in recommendations for the selection of indicators of 'high relevance' as proxy for sustainable land use. They include soil organic matter, biodiversity, water availability and water quality as environmental indicators, energy use in agriculture and agro-diversity as indicators for land use intensity, forest loss, wetland loss, and grassland to cropland conversion as indicators for land use change/conversion, and land quality weighted footprints as improved system indicators.

Against this background, following the recommendations from the expert workshop this study included the following priority indicators: cropland and grassland footprint weighted by land quality (system indicator), energy use in agriculture (proxy for land use intensity), irrigation water use in agriculture classified by water scarcity/security and deforestation attributable to pasture expansion. While all these indicators are considered meaningful and quantifiable to extend and enhance the policy relevance of area-based land footprints, the scope of this study was limited to provide examples of a quantification for a sub-set of those, specifically to demonstrate the application of a system indicator and to quantify and track through the commodity chain the deforestation extents of the period 1995 to 2010.

System indicators highlight the crucial importance of land quality for meaningful interpretation of land footprints. This is especially true for grassland where, compared to cropland, an even wider range of land qualities and productive capacities occurs throughout the world. Moreover, statistical data record cropland extents and use in some detail (annual/perennial crops, fallow period), but data are in most countries not available for grassland extents actually used for livestock grazing and definitions for grassland and pasture differ across regions and spatial land use databases.

National level feed balance calculations undertaken in the context of the footprint calculation in the current study suggest that the fraction of available biomass from the statistical pasture areas needed to meet the energy requirements of national ruminant livestock herds varies across countries. Though important for environmental impacts and appropriation of ecosystem services, such considerations could not be included in quantifying grassland footprints due to paucity of available global data. Therefore land qualities and productive capacity of cropland areas are more robust and less uncertain compared to estimates for grassland and pasture areas. An improvement for grassland footprints could be achieved by a combination of national feed balance calculations and land quality estimates and an assumptions on livestock densities.

Due to large differences in the trade share of different commodity groups, the composition of the German and EU footprint and the self-reliance ratio varies depending on whether unweighted or quality weighted extents are used in the calculations.

Land quality and yields are relatively high in Germany and large tracks of the EU compared to other agricultural regions, for instance vast arid and semi-arid areas in the subtropics and tropics including those from which the EU sources its imports. In consequence a land quality weighted footprint increases the relative share of the component of the land footprint which relies on distant land resources.

This effect can for instance be observed for the consumption of non-food products since they rely, compared to food-products, to a larger extent on imports. The relative increase of crop-based food use in the cropland quality weighted footprints is mainly due to stimulants (coffee, cacao, tea), which come from land in sub-humid and humid tropical regions with year-round growing conditions and a rather high production capacity and to a lesser extent the commodity groups fruits/vegetables/spices, primary oil crops and vegetable oil. On the other hand imports of selected commodity group like hides/skins/wool into Germany and the EU decrease when measured in land-quality weighted footprints because of their origin from countries with large grassland extents of low productive capacity (e.g. Mongolia, China).

The deforestation footprints reveals for the first time a quantification of Germany's and the EU's contribution to global deforestation. It should be noted that the majority of global deforestation occurred in the tropical zone, a hot spot of loss of biodiversity during the last two decades and an important source of anthropogenic greenhouse gas emissions. Germany's and the EU's deforestation footprint for the period 1995 and 2010 amounts to 0.94 Mha and 6.2 Mha respectively. The majority of the EU's deforestation footprint (90 % for Germany and 84 % for the EU) is due to cropland expansion causing deforestation in countries from which food or feed products are imported. The remainder is associated with ruminant livestock consumption from increasing livestock herds that directly or indirectly resulted in forest conversion to pastures.

Some 10 % (or 5.2 Mha) of global food and feed crops attributed to expanding cropland causing deforestation between 1995 and 2010 due to expanding cropland are embedded in EU consumption, about 25% higher than the EU28 share in global population, which was 8.4% in 1995 and down to 7.3% in 2010. Almost half (2.4 Mha) is connected to livestock based diets via protein feed imports. Other important commodities include coffee/cacao/tea, vegetable oil and fruits/vegetables/spices embedded in the EU citizen's diets as well as various non-food uses (e.g. rubber and other industrial crops, vegetable oil for the oleo-chemical industry, alcohol and tobacco).

To broaden the analysis, a further step should be to screen specific identified most important items in the consumption patterns against a more detailed list of qualitative and quantitative environmental and social indicators of relevance for sustainable land use. Such an assessment can benefit from the previous steps of the analysis by limiting qualitative research to the most relevant elements of the quantified land footprints. For example, results for Germany suggest to focus additional qualitative research on the sustainability of some specific sectors:

- the livestock sector, by far the largest component of the German land footprint accounting for almost half of the cropland footprint (or two-thirds of the food-related cropland footprint) and the additional grassland footprints of ruminant livestock products (beef, milk). Moreover, consumption of livestock products is connected with half of the deforestation footprint.
- the oil crop sector, contributing to the land embedded in livestock products and the non-food industry and being heavily dependent on imported commodities especially from South America (soybean) but also Southeast Asia (oil palm) and Eastern Europe (rapeseed).
- the commodity group of stimulants (coffee/cacao/tea), which must be imported from tropical/sub-tropical regions accounting for almost one fifth of cropland embedded in imports and some 17% of the crop-based food.
- the observed trend in the non-food contribution of the cropland footprint, which increased from 19% of the footprint in 1995 to a current 24% (year 2010) and stems to more than four fifth (86%) from commodities produced on foreign cropland.

In addition, it will be useful land important to study in more detail the differences in the effectiveness of using cropland and pasture resources (i.e. apparent yield gaps) and their meaningful interpretation with regard to land footprints and environmental impacts. This will likely require the use of more detailed geographical databases, beyond country level statistics, and the application of spatial downscaling and modelling methodologies.

The current study has focused on the environmental dimension of land footprints. However, a comprehensive assessment of sustainable land use must also include socio-economic indicators. Although difficult to quantify, because of data limitations (e.g. land tenure, access to land and water, child labour) and/or conceptual issues (e.g. fairness, governance), we see the need for further research in particular for those consumption items/components with a high environmental impact and a high degree of dependence on foreign sources, namely livestock consumption, the oil crop sector, and the coffee/tea/cacao commodity group.

The indicators developed in this study provide useful information required for achieving several of the recently adopted 'Sustainable Development Goals (SDGs) (UN, 2015). Goal 2 "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" is directly related to agricultural production, management of cropland and grassland, and food consumption including dietary patterns. Irrigation development is key to Goal 6 "Ensure availability and sustainable management of water and sanitation for all". Goal 12 "Ensure sustainable consumption and production patterns" includes the target to achieve by 2030 the sustainable management and efficient use of natural resources. The sub-goal 12.8 is to ensure by 2030 that people at large have the relevant information and awareness for sustainable development and lifestyles in harmony with nature. The deforestation and livestock footprint is connected to Goal 13 "Take urgent action to combat climate change and its impacts." Identifying measures toward achieving those SDGs can greatly benefit from the here presented approach to quantify land footprints and their quality and impact-oriented extensions.

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9 Annex 1: Role of socio-economic indicators

While the project objectives were focused on the identification of environmental impact-oriented indicators, any comprehensive assessment of sustainable land use would also need to include socio-economic indicators. The box below provides an overview of relevant issues.

Box: Overview of socio-economic and cultural indicators of land use

Issue	Indicator*	Proxies/Indicator measurement
Food security	Fair distribution of provisioning services	Energy content (in calories) in relation to land requirements
		“Bio-productivity” footprint indicator (see chapter 5.3.3.3)
	Malnutrition	(changes in) % of undernourished people
Land Governance	Access to land/land tenure/property rights	Share of women and men with equal and secure access to land
	Corruption	Corruption Perceptions Index
Recreation	Abundance/quality of recreation sites	Number of visitors Visitors opinion, income from ecotourism
Cultural value	Storage and protection of evidence of the cultural history of humankind	Abundance and score of objects/sites/landscapes (Marques 2013)

9.1 Food security

The right to food as recognized in the UN Declaration of Human Rights is vital for the enjoyment of all other rights. Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life (FAO 2014b). Indicators for global food security include e.g. food prices and food price volatility, malnutrition and changes in malnutrition.

However, with rising populations, rising demands for biomass in different sectors (food, feed, fuel fibre) and changing diets with a globally increased demand for meat and animal products global food security also depends on the fair distribution of available land resources.

Indicators to assess the fair distribution of land resources/provisioning services of land are not yet widely discussed in literature. Below we provide two potential proxies for this indicator.

Energy content (in calories) in relation to land requirements

The relevance of this indicator lies in the very basic fact that food security can be achieved with different diets and that food products have different land requirements per calorie and megajoule (MJ). Similarly, the amount of protein can be an alternative proxy to energy content. However, while energy or protein content may be a useful measurement for food and feed, it is unsuitable to non-food products such as cotton and wood.

This indicator can provide information about the land requirements for food consumption (see Table 16 below for examples), the efficiency of land resources needed to produce them and would allow comparisons between consumers/per capita assessment of countries.

Table 18: Examples of land use requirements of food (according to (Bringezu, S., Schütz, H. 2009) cited in (SRU 2012))

Food product	Land requirement (m^2/MJ)*
Beef	2.09
Pork	0.79
Cow milk	0.72
Eggs	0.60
Poultry	0.54
Vegetables (open land)	0.34
Bread	0.19
Apples	0.16
Crop/cereals	0.12
Potatoes	0.11

* land requirements calculated for German consumption considering international land requirements due to global trade of agricultural products

More specifically, this indicator would put the energy content (measured in calories or MJ) of a product in relation to the land that is needed for their production.

While this indicator would be easy to communicate to consumers, it also has conceptual shortcomings such as the lack of information with regard to health choices and balanced diets. For example, products with little land requirements per calorie are not necessarily healthy (e.g. sugar and trans-fats). Similarly, undernourishment results in low land requirements, but is not desirable.

9.2 Land Governance/Land tenure/Access to Land

Land degradation is often linked to poor or inadequate governance regimes (UNCCD Secretariat 2013) and socio-economic aspects. For example, achieving food security for poor small-scale farming communities requires action against land degradation as they are the ones usually occupying degraded lands (IASS, UBA, EC, Global Soil Forum 2013). Security of access to land and the protection of land rights are also crucial.

However, most indicators can hardly be linked to primary production (e.g. the Corruption Index that is only available on national level but obviously not for specific products).

9.2.1 Land tenure/land access

With the agreement of the “Voluntary Guidelines on the responsible Governance of tenure of land, fisheries and forests in the context of national food security” in 2012 (FAO CFS 2012) and the ongoing negotiations about the Sustainable Development Goals (SDGs) land tenure and access to land are currently widely discussed.

Suggestions for socio-economic indicators for soils and land within the SDGs include for example (IASS, UBA, EC, Global Soil Forum 2013):

- reduction in land related conflicts
- share of women and men with equal and secure access to land
- restoration activities targeting people below their countries poverty line

In addition, the Global Land Tool Network (GLTN 2014) suggests the following indicators:

- percentage of women and men, indigenous peoples and local communities and businesses with legally recognized evidence of tenure
- extent to which the national legal framework provides women and men equal rights to land resource and property
- extent to which the national legal framework recognizes and protects legitimate land rights and uses derived through a plurality of tenure regimes

9.2.2 Corruption

Where land governance is deficient, high levels of corruption often flourish. Weak land governance tends to be characterized by low levels of transparency, accountability and the rule of law. Under such a system, land distribution is unequal, tenure is insecure, and natural resources are poorly managed (Transparency International/FAO 2011).

In order to monitor corruption in countries, Transparency International's „Corruption Perception Index" can provide useful information. However, this nationally applied and more general indicator has no direct link to land use, which makes its interpretation for the land footprint quite difficult.

10 Annex 2: Overview of environmental impact-oriented indicators related to land use

In addition to the brief explanations within chapter 3 that provided an overview of environmental impact indicators for sustainable land use , this Annex compiles further information for all indicator categories, as shown below.

In the following, each chapter on categories and subcategories includes an *introductory section* that gives an overview about the scope of available indicators, including those that are not further analysed within this working paper. If indicators seem particularly suitable as a potential priority indicator this is indicated.

More specifically, we describe for each indicator

- its main characteristics, including the indicator's suitability to provide relevant information to evaluate impacts on different environmental goods (linking to existing studies and approaches where the indicator is used where relevant);
- data requirements / how it is measured.

10.1 Environmental Impacts

Indicators are assessed in this study due to their indication of impacts on

- Biodiversity
- Soil
- Water
- Climate / Air[28]

Those four environmental categories[29] that are also the subject of the analysis within this chapter are also subject of impact assessments according to the European Environmental Impact Assessment (EIA) Directive[30] (which was recently updated and now also includes land as an environmental factor to consider) and the EU's Strategic Environmental Assessment (SEA) Directive (Directive 2011/92/EU). They are also the core subjects ("*Schutzgüter*") of Germanys Federal Nature Conservation Act ("*Bundesnaturschutzgesetz*").

10.1.1 Biodiversity

Biodiversity plays an essential role to maintain basic ecosystem processes and supporting ecosystem functions (Marques et al. 2013) and changes in biodiversity can influence the supply of ecosystem services. It is widely acknowledged that biodiversity is an important indicator to evaluate the sustainability of land use.

However, there is no global, harmonized observation system for delivering regular and suitable data on biodiversity change (Pereira et al. 2013). Despite progress in digital mobilization of biodiversity records and data standards, there is still insufficient consistent national or regional monitoring as well as sharing of such information (Marques et al. 2013).

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[28] While land use has a big impact on climate and climate change, air as an environmental good is not as much related and hence not included in the analysis of this paper.

[29] Other subjects include cultural heritage and the landscape, material assets and human health – these however are not core environmental media/goods but also reflect cultural and social values of environmental goods.

[30] Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment.

Moreover, as a rather broad and cross cutting issue biodiversity can be expressed in a wide range of different indicators, which impedes a straightforward and widely applied indicator approach to assess biodiversity across regions. Hence, monitoring of biodiversity is often confronted with the question: What to measure exactly and how making it comparable to other areas?

Box: Selection of land use relevant SEBI biodiversity indicators (adapted from European Environment Agency 2011)

Headline indicator	**SEBI specific indictor**	**Relation to land use**
Trends in the abundance and distribution of selected species	Abundance and distribution of selected species a. Birds b. Butterflies	The abundance of bird species, especially farmland birds, serve as a good proxy to monitor the intensity of agricultural land use (Eurostat data) and biodiversity in general[31]
	Red List Index	The abundance of red list species can show the natural value of land (use) in a certain area (worldwide)
Trends in genetic diversity of domesticated animals, cultivated plants, and fish species of major socioeconomic importance	Livestock genetic diversity	Indicator to potentially qualify livestock husbandry (pastures) with regard to genetic diversity.
Connectivity/fragmentation of ecosystems	Fragmentation of natural and semi-natural areas	Land use causes fragmentation of habitats which is a major cause of biodiversity loss.
Area of forest, agricultural, fishery and aquaculture ecosystems under sustainable management	Forest: growing stock, increment and fellings	Basic measures to monitor sustainable forest management
	Forest: deadwood	Content of deadwood in forests not easy to measure/monitor but significant for (species and structural) biodiversity
	Agriculture: nitrogen balance	See chapter on fertilizer use
	Agriculture: area under management practices potentially supporting biodiversity	Requires regionally specific list of “sustainable practices”, then relatively easy to detect

The Group on Earth Observations Biodiversity Observation Network (GEO BON) has proposed a set of Essential Biodiversity Variables (EBVs), which form the minimum biodiversity aspects that should be used in order to study and monitor biodiversity change, based on their suitability across taxa and ecosystems, their temporal sensitivity and their feasibility (Pereira et al. 2013):

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[31] The Pan-European Common Bird Monitoring Scheme (PECBMS) aims to explore the use of bird population trends as indicators of biodiversity, developing an annually updated assessment of the mean change in farmland and woodland breeding bird populations in Europe, which covers 163 common and widespread species. Data is gathered through the collaboration between individuals and organizations, as the European Bird Census Council (EBCC) and BirdLife International.

- Genetic composition
- Species populations
- Species traits
- Community composition
- Ecosystem structure
- Ecosystem function

While the last two categories focus on broader services and characteristics of ecosystem services, the other categories could be regarded as biodiversity aspects in a stricter sense. They encompass measures and indicators related to living or biotic entities (individuals, species and populations).

There are also specific indicators discussed and used on EU level – mainly by the EEA and EUROSTAT – to monitor the trends and losses in biodiversity. In 2005, the EEA started an initiative together with other EU and international institutions to "Streamline European Biodiversity Indicators" (SEBI; see European Environment Agency 2011). Among the 26 SEBI indicators in total, some are particularly relevant for the assessment of the sustainability of land use as shown in the box below (including the respective "Headline indicator").

This overview shows that within the SEBI indicators some relate to land management (nitrogen balance, stocking density, dead wood in forests) while others directly aim to measure species diversity and distribution, habitat fragmentation and protected areas. As land use and land management are stressed within chapter 5.3 and 5.4, we focus on direct biodiversity indicators within this chapter.

10.1.1.1 Abundance and distribution of (selected) species

Relevance

Abundance and distribution of species is a very common biodiversity indicator. In Germany it is for example used within the National Sustainability Strategy that uses the abundance of certain bird species as a key and representative indicator for biodiversity. Monitored over time conclusions can be drawn about the change of abundance and distribution (in many cases the biodiversity loss) in a certain area. The species selected for monitoring are often so called "keystone" species, i.e. species that play a critical role in maintaining the structure of an ecological community, affecting many other organisms in an ecosystem and helping to determine the types and numbers of various other species in the community.

Data requirements/measurement

The data required depends on the approach chosen that focuses either on selected species (e.g. keystone species such as farmland birds or **threatened species of the IUCN red list**), or **plant and animal species richness** (in some indicators limited to **Livestock genetic diversity**), i.e. an indicator that is built on a broad variety of species.

Alternatively "**Mean Species Abundance**" (MSA) is widely applied as a concept in key analytical frameworks for biodiversity loss, for example in mapping biodiversity across the EU (Maes et al. 2014) and in the Natural Capital Index Framework (NCI) mainly developed by the Netherlands Environmental Assessment Agency.

There are also some interesting integrated approaches that build on species richness but relate this to either land use types (Biodiversity Damage Potential) or the remaining mean species abundance (MSA) of original species, relative to their abundance in pristine or primary vegetation (GLOBIO 3 model). Others link data on threatened species to supply chains of various commodities (Lenzen et al. 2012). They are described below.

Integrated approaches including biodiversity indicators on species abundance and distribution

A more integrated approach for a biodiversity indicator than the selection made be SEBI is from Switzerland and directly relates land use to biodiversity impacts. Based on an **LCA approach**, the indicator proposed by de Baan, Alkemade, and Koellner (2013) addresses land occupation impacts, quantified as a **biodiversity damage potential (BDP)**. The key measure behind this indicator is animal and plant species richness, which is compared between land use types and their (semi-)natural regional reference situations and thereby examines impacts of types of land use within biomes on biodiversity. However, this measure cannot be calculated (yet) per unit of output (de Baan, Alkemade, and Koellner 2013). For their calculations, de Baan, Alkemade, and Koellner (2013) used data on multiple species groups derived from a global quantitative literature review and national biodiversity monitoring data from Switzerland. While the strength of this indicator is its wide (global) applicability, De Baan et al. (2012) also see limitations on indicators building on species richness such as their high dependence on sampling effort, missing information on abundance and no link to conservation targets. Due to data and information gaps, for example on regeneration times of ecosystems and transformation impacts, the approach can be seen as a “first attempt to quantify land use impacts on biodiversity within LCA across world regions (…)” (de Baan, Alkemade, and Koellner 2013). Frischknecht, Itten and Büsser Knöpfel (2013) see a certain flexibility in bridging data gaps for the BDP through by using biome-specific averages.

In an earlier approach to assess the global loss of biodiversity, a combined model was developed, which is built on a set of equations linking environmental drivers and biodiversity impacts (cause-effect-relationships) (Alkemade et al. 2009). This so-called **GLOBIO3 model** describes biodiversity as “the **remaining mean species abundance (MSA) of original species, relative to their abundance in pristine or primary vegetation**” (Alkemade et al. 2009). Conceptually, the model builds on various preceded efforts to assess the loss of global biodiversity. Its data are mainly derived from the IMAGE model[32], which is widely applied at international level to calculate changes in land and land use. The GLOBIO3 model can assess the impacts of environmental drivers on MSA and their relative importance, expected trends under various future scenarios, and the likely effects of various responses of policy options. Being a model itself, the suitability of GLOBIO3 for the land footprint indicator is not directly obvious. The data of land use (change) from IMAGE could be a valuable source itself, but the scenarios conducted by the model are not of direct relevance for the further qualification of the land footprint indicator, unless explicit scenarios for a particular region are run by the model to gain further insights on the trends in regional biodiversity loss. In other words, the assessments made by GLOBIO3 do not reveal a specific indicator, which could be of use to depict the loss on biodiversity within the land footprint indicator. Moreover, the authors point towards a broad range of uncertainties inherent to the use of GLOBIO3 (cause-effect relationships, drivers and underlying data) (Alkemade et al. 2009). However, it might be worth to further analyze the suitability of MSA as a proxy for the relative biodiversity loss to be considered also in the land footprint.

Another approach worth considering is the one developed by Lenzen et al. (2012) who **linked data on threatened species to supply chains of various commodities** across the globe. The study showed that 30% of global species threats are due to international trade, invasive species not included in this figure. A major cause of this are the consumption patterns in developed countries which effect species through their demand of commodities that are ultimately produced in developing countries.

In their model, the authors integrated the **IUCN Red List of Threatened Species** plus a compatible list of **threatened bird species** from Bird Life International with a new high-resolution global multi-region input–output database on economic activities (Lenzen et al. 2012). They link 25,000 animalia

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[32] For further information, see: http://themasites.pbl.nl/tridion/en/themasites/image/overview/components/index-2.html

species threat records to more than 15,000 commodities produced in 187 countries and evaluated more than 5 billion supply chains in terms of their biodiversity impacts.

The approach Lenzen et al. (2012) chose is particularly interesting, because they link data on threatened species with relevant commodities and their supply chains across the globe – an approach which might fit well to the approach of the land footprint. However, the effort and the data requirements seem extremely high.

10.1.1.2 Fragmentation of natural and semi-natural areas

Relevance

Habitat fragmentation can be caused by geological processes that slowly alter the layout of the physical environment or by human activity such as land conversion, which can alter the environment much faster and cause biodiversity loss. One of the major ways that habitat fragmentation affects biodiversity is by reducing the amount of available habitat for all organisms in an ecological niche. Habitat fragmentation also invariably involves some amount of habitat destruction. Mobile animals (especially birds and mammals) retreat into remnant patches of habitat. This can lead to crowding effects and increased competition. The remaining habitat fragments are smaller than the original habitat. Species that can move between fragments may use more than one fragment. Species which cannot move between fragments must cope with what is available in the single fragment in which they ended up.

Data requirement/measurement

One commonly applied measure to monitor landscape fragmentation is the **effective mesh size**, which has proven as most suitable compared to other measures due to its mathematical characteristics and its intuitive interpretation (Jaeger 2000). Moreover, it aggregates the information on landscape fragmentation into a single value that can be easily obtained and interpreted (Jaeger et al. 2008).

The effective mesh size can be defined as the likelihood that any two randomly chosen points in the region under observation may or may not be connected. The more barriers (e.g., roads, railroads, urban areas) erected in the landscape, the less chance that the two points will be connected (Jaeger 2000). As a mere mathematical measure the mesh size needs empirical underpinning, but it has demonstrated its implacability in the Swiss Monitoring System of Sustainable Development (MONET) (Jaeger et al. 2008). Also the German Federal Environment Agency (UBA) has already adopted the effective mesh size ("Mittlere effektive Maschenweite") to propose limits to landscape fragmentation in Germany (Penn-Bressel 2005; Umweltbundesamt (UBA) 2003; Schönthaler and Pieck 2013). So far, the effective mesh size has been mostly applied at regional level, but attempts to extend its application to the national scale are underway, e.g. in Germany[33] and in Canada. More recently, the EEA has published a report on landscape fragmentation, where the effective mesh size has been applied across all 28 EU Member states (European Environment Agency 2011).

Habitat fragmentation can be expressed with an indicator related to the amount of **unfragmented low-traffic areas** ("Unzerschnittene verkehrsarme Räume (UZVR)") as a percentage of total land (Schönthaler and Pieck 2013).

10.1.1.3 Protected areas

Relevance

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[33] A different example to assess habitat fragmentation used in many parts of Germany is an indicator on "unfragmented low-traffic areas" ("Unzerschnittene verkehrsarme Räume (UZVR)") as a percentage of total land (see also Schönthaler and Pieck 2013)

The creation of protected areas and area networks helps to reduce biodiversity loss and provides significant contributions to global conservation efforts. However, despite the fact that the surface area of designated protected areas has steadily increased since 1970, the rate of biodiversity loss continues to increase (IUCN 2014). The relevance of an indicator that informs about the change in size (and number) of protected areas is therefore not very high, but provides additional helpful information.

The discrepancy between the trends in increasing protected area coverage but declining biodiversity over the last four decades may relate to two key factors: (1) the degree to which protected areas deliver biodiversity outcomes; and (2) the degree to which significant biodiversity is represented within protected areas (IUCN 2014) (i.e. that some protected areas might not be very high in biodiversity compared to other unprotected areas).

Another downside of protected areas as an indicator for biodiversity is that the level of demand/requirements for biodiversity protection is very different in the different protected area categories. For example some are very strict (e.g. inner zone of national parks), while others even allow agricultural activities with low protection standards, e.g. the German "areas of outstanding beauty" ("*Landschaftsschutzgebiete*").

Data requirement/measurement

This indicator can be measured as **% of protected land** and might be further differentiated according to the different categories of nature protection (e.g. protected wetlands, biosphere reserves, national parks etc.).

10.1.1.4 Livestock Diversity

Relevance

Genetic livestock diversity relates to the biodiversity within the livestock sector. More than 35 species of birds and mammals have been domesticated for use in agriculture and food production, and there are more than 8,000 recognized breeds. Livestock keeping is an important livelihood activity for hundreds of millions of people around the world, including an estimated 70% of the world's rural poor. Livestock also provide a number of services within the ecosystems of which they form part. Grazing animals such as cattle, goats, sheep and horses stimulate plant growth, remove excess biomass, and contribute to nutrient cycling and seed dispersal. Genetic diversity in livestock species provides vital options for adapting livestock production to future challenges (Biodiversity Indicator Partnership 2014). However, currently food production systems are based on just a very limited number of species, while other breeds and species are at risk of extinction. Increased livestock diversity therefore improves resilience for future food production.

Data requirement/measurement

"**Livestock Genetic Diversity**" is used to assess the Aichi target 13 of the UN CBD (Convention of Biological Diversity)[34].

This category is translated into a set of three indicators, all suitable to measure "Livestock Genetic Biodiversity":

a) The **number of locally adapted breeds** (as a basic measure of breed richness)[35].

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[34] It is also an indicator of the EEAs "Streamline European Biodiversity Indicators" (SEBI)

[35] Breeds are considered to be "locally adapted" if they have been in a given country for a sufficient time to be genetically adapted to one or more of traditional production systems or environments in the country. Breeds that are not locally adapted are described as "exotic". It will only change if locally adapted breeds become extinct or if additional breeds qualify for the locally adapted category (Biodiversity Indicator Partnership 2014)

b) The **proportion** of the total population accounted for by **locally adapted and exotic breeds**

c) The number of **breeds classified as at risk**, not at risk and unknown (Proportion of the world's breeds reported to the FAO by risk status category).

This indicator set agreed under the CBD Aichi targets is intended for calculation at global, regional and national levels. It has not yet (as of July 2013) been fully calculated, because countries have not yet classified their breeds as locally adapted or exotic (Biodiversity Indicator Partnership 2014).

10.1.1.5 Landscape Diversity

Relevance

Linear landscape elements, such as ditches, hedgerows, lines of trees and field margins function as ecological infrastructure for species within agricultural landscapes. Such landscape elements are thus also important to distinguish between homogeneous landscapes, which are often intensively managed, and heterogeneous landscapes.

Data requirement/measurement

A proxy for this indicator can be the **percentage of structural elements in the area**. While data availability and comparability on the global level is low, this indicator is common to use in the EU and Germany. On a European level it is important as structural elements are a requirement within the Cross Compliance requirements (GAEC, Good agricultural and environmental conditions) within the EU Common Agricultural Policy. Furthermore landscape diversity is also discussed as an indicator within the "Hemeroby" composite indicator (see Fehrenbach 2014), with 5 categories for different levels for landscape diversity ranging from "Spaciously monotonous unstructured landscape" to "Landscape with a spaciously variform character, a parkland-like appearance rich of wood; high integration of field, meadows and woods".

10.1.2 Soil

Sustainable land use is closely connected to the sustainable use of soils, essentially constituting the land and basic resources for sustainable land use. Soils are of high environmental and socio-economic importance due to their manifold vital functions: food and other biomass production, storage, filtration and transformation of many substances including water, carbon, nitrogen. Soil has a role as a habitat and gene pool, serves as a platform for human activities, landscape and heritage and acts as a provider of raw materials. Therefore, the degradation of soil and land that takes place in large parts of the world is a relevant problem. Soil threats that cause soil degradation – and are therefore relevant entry points for impact-oriented indicators within this project – are:

- Loss of soil organic matter
- Wind and water erosion
- Compaction
- Salinization
- Landslides
- Contamination
- Sealing

A combination of some of these threats can ultimately lead arid or sub-arid climatic conditions to desertification.

From this range of pressures the loss of soil organic matter – mainly measured in soil organic carbon – stands out as a possible key indicator. Given its relevance for soil functions, biodiversity, climate and productivity , the indicator "change in soil organic matter/soil organic carbon" is frequently recognized as “the best stand-alone indicator for soil quality”(Frischknecht, Itten, and Büsser Knöpfel 2013).

The loss of soil organic matter is also strongly interlinked with soil erosion. Given their global relevance and strong impacts on the environment and productivity, we will therefore focus on soil erosion and soil organic matter in the following subchapters.

The issue of soil sealing is taken up within the chapter “Land Conversion” under the indicator heading “land take/built up land”.

10.1.2.1 Soil organic matter

Relevance

Soil organic matter (SOM) is the organic fraction of the soil that is made up of decomposed plant and animal materials as well as microbial organisms, but does not include fresh and un-decomposed plant materials, such as straw and litter, lying on the soil surface.

Soil organic matter influences properties like buffer capacity, soil structure and fertility. An indicator focusing on soil organic matter losses also allows drawing conclusions about the greenhouse gas emissions of agricultural practices (e.g. high loss of SOM through peat land drainage and deforestation). At the same time it is a good indicator for soil health and soil biodiversity.

The annual rate of loss of organic matter can vary greatly, depending on cultivation practices, the type of plant/crop cover, drainage status of the soil and weather conditions. There are two groups of factors that influence inherent organic matter content: natural factors (climate, soil parent material, land cover and/or vegetation and topography), and human-induced factors (land use, management and degradation) (EU JRC 2013). An example for the influence of land use practices are tillage practices: Minimum tillage practices prevent losses of SOM, prevent carbon emissions from the soil, but also prevent erosion and nutrient runoff, thereby also protecting water resources.

So while soil organic matter content does not fully consider all aspects of soil functions, it is qualified as a key soil quality indicator, especially for assessing the impacts on fertile land, agriculture and forestry systems. Frischknecht, Itten, and Büsser Knöpfel (2013) present soil organic matter as a robust indicator for soil quality; and highlights that SOM has been often recognized as the best stand-alone indicator for soil quality. Also, they consider the deficit of SOM as an appropriate indicator for “Biotic production potential” and “Ecological Soil Quality” within an evaluation framework for Ecosystem services.

Data requirements/measurement

Soil organic matter content can be measured directly from soil samples, calculated using local datasets and locally adjusted models, and estimated from literature values for different areas and crops.

However, in many cases **soil organic carbon** data is used to measure SOM. Soil organic matter and soil organic carbon are often confused and mistakenly used interchangeably. However, soil organic carbon (SOC) is only the organic carbon associated with soil organic matter and a component correlated with organic matter that derives mainly from decaying plant materials of organic matter. Soil carbon can also be present in inorganic forms, e.g. lime or carbonates in some soils in the drier areas. SOM on the other hand also includes other elements such as hydrogen, oxygen and nitrogen. Soil organic carbon makes up about 58 per cent of the mass of organic matter and is usually reported in a soil analysis report as the concentration (i.e. per cent) of organic carbon in soil (Chan 2008)[36].

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[36] SOC results are usually expressed as % C by weight (i.e. g C per 100 g of soil). SOC results can be converted to soil organic matter (SOM) level by multiplying SOC value by a conversion factor of 1.72. This assumes that SOM present in soil, on

For regions where data on soil organic carbon/soil organic carbon is not available (such as in many developing countries), the use of colour cards is discussed. Colour cards, such as the Munsell colour charts, are based on the fact that soil colour is closely correlated with organic matter that derives mainly from decaying plant materials.

With regard to data availability on global level, there are some new initiatives underway (but also better use of technologies, such as remote sensing), that can help to create a better database to assess soil organic carbon in soils in the future including regular updates, which should make it easier to generate data about soil carbon losses: For example the Global Soil Partnership (GSP) aims to enhance the quantity and quality of soil data and information (see McKenzie et al. 2013). Moreover, efforts are underway by ISRIC (the World Soil Information Institute) and others to improve the availability for soil data. Most importantly, ISRIC has developed the Global Soil Information Facilities (GSIF), a collection of databases, tools and associated cyber infrastructure for automated soil mapping.

10.1.2.2 Wind and Water Erosion

Relevance

Soil erosion decreases productivity of soils and degrades ecosystems. Soil erosion is a severe problem globally and in the EU: According to the FAO, globally "moderate to severe soil degradation affects almost 2,000 million hectares of arable and grazing land" – an area larger than that of the United States and Mexico combined. "More than 55 percent of this damage is caused by water erosion and nearly 33 percent by wind erosion" (FAO 1995 p.199). Water erosion is also a worrying pressure in the EU and is estimated to affect 1.3 million km^2 in Europe, an area equivalent to 2.5 times the size of France (European Commission 2012a).

Physical factors such as climate, topography and soil characteristics are important in the process of soil erosion, but even more important factors are the land cover and the agricultural practices.

Organic matter is a small fraction of soil mainly present on the soil surface. Erosion gradually depletes organic matter and decreases soil productivity. When organic matter is lost, soils tend to lose their physical structure. The degradation of soil structure makes the soil hard, compact and cloddy. The soil aeration, water-holding capacity and permeability are also decreased. Decreased aeration means less oxygen available for plant roots to grow. Decreased water availability also means less water available for healthy plant growth. When soil permeability decreases, less water will soak into the soil and more will run off. Beneficial organisms that suppress disease and break down organic residues will not function well due to reduced oxygen and water in soil. This in turn will reduce nutrient storage and supply abilities of the soil (University of California-Davis 2014).

Data requirements/measurement

Soil erosion can be measured and/or estimated in **the amount of topsoil loss per ha and year.**

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average, is made up of 58 % carbon. Very often though it is more practical to express SOC on per ha basis, namely as tonnes C per ha (Chan 2008, 200).

In terms of data availability the "Global Assessment of Human-induced Soil Degradation" (GLASOD) is to date the only global effort to map soil degradation. It measures soil degradation extent and degree, including water erosion and wind erosion. However, the GLASOD project finished 1990 and is therefore out of date. However, there are new promising initiatives and efforts to improve the data basis for soil quality assessments (see chapter on soil organic matter/soil carbon).

10.1.3 Water

Water availability and quality is essential for agricultural production and agriculture is an important user of water, with 70% of total global fresh and groundwater use is for agricultural purposes (FAO 2011).

The unsustainable use of water in agriculture has various external effects and leads to different environmental problems. Overexploitation of water resources can lead to falling groundwater levels and depleted surface waters, which damages associated ecosystems and the services they provide and can lead to conflicts over diminishing water resources.

Land use practices also have a large impact on water quality and can lead to losses of biodiversity and degradation of ecosystem services (Srebotnjak et al. 2010).

Added nutrients from sewage, manure, and fertilizer runoff can lead to eutrophication. Pesticides, sediments, bacterial contamination and pharmaceuticals in runoff water from urban and rural land use may similarly affect water quality. Also forest management practices can disrupt nutrient cycles and can increase runoff and concentrations of dissolved nutrients in adjacent streams and lakes.

The ecological impacts of water use also heavily depend on regional factors such as regional use patterns, temporal and spatial availability, and consumptive vs. non-consumptive use (Pfister, Koehler and Hellweg 2009).

10.1.3.1 Water quantity and scarcity

Indicators in this category touch on issues of the quantity of water use. This can be done by putting withdrawals in relation to water availability and expressed as **"% of withdrawals to total renewable water resources"**, as in the FAOSTAT database and used in the EEAs "**Water Exploitation Index (WEI)**". According to the EEA an index of over 20 % usually indicates water scarcity (European Environment Agency 2008).

There are many other methodologies for this type of indicator which allow for precision on different scales (Frischknecht, Itten, and Büsser Knöpfel 2013). Pfister, Koehler and Hellweg (2009) developed a **Water Stress Index** to indicate whether a product's production was contributing to water stress and negative ecological impacts based on existing environmental accounting models.

Another water stress indicator is the **Falkenmark Water Stress Indicator**. According to this indicator a country or region is said to experience "water stress" when annual water supplies drop below 1,700 cubic metres per person per year (Falkenmark, Lundquist, and Widstrand 1989a).

The **"water dependency ratio"** is a useful tool to investigate water sovereignty, i.e. the (lack of) dependence on foreign water imports and can also be seen as a socio-economic indicator. It measures the **percentage of total renewable ground- and freshwater water resources originating outside the country** (Srebotnjak et al. 2010).

10.1.3.2 Water quality

Various water quality indexes have been developed, for example UNEP's **Global Water Quality Index,** a composite indicator that includes the following water quality indicators:

- Biochemical oxygen demand or B.O.D is the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic material present in a given water sample at certain temperature over a specific time period.
- **Acidification**: **pH**, which is the measure of the acidity or alkalinity of a water body, is an important parameter of water quality that it can affect aquatic organisms. pH is also important in assessing the suitability of water for drinking.
- **Salinisation**: **Conductivity** is a measure of the ability of water to carry an electric current which is dependent on the presence of ions. It is often used as an indirect measure of salinity and total dissolved solids (TDS). Total dissolved solids can also be estimated from conductivity by multiplying conductivity by an empirical factor (APHA 1995). Increases in salinity have been shown to reduce biodiversity and alter community composition by excluding sensitive (Weber-Scannell and Duffy 2007).
- **Nutrient pollution**: Nitrogen and Phosphorous: **Increases in nitrogen and/or phosphorus in natural waters**, largely as a result of human activities in the drainage basin (e.g. from agricultural runoff), can result in increased biological productivity of a water body. Nutrient increases can lead to shifts in aquatic community composition and loss of endemic species (see also chapter on “fertilizer use”).

The parameters used in the UN’s Global Water Quality Index to quantify water quality on a country by country basis were chosen to “represent a number of key environmental issues that have global relevance” (UNEP 2010).

Schönthaler and Pieck (2013) suggest several other indicators for water quality, such as the **amount of water bodies** (ground water or surface water) **that are in “good” ecological condition**. These indicators are not taken into further consideration here because of their lack of quantifiability in terms of product or consumption impact, data unavailability or incoherence, or lack of harmonized standards and definitions at a national or international level.

The ratio of observed to maximum allowable level of pollutants can be another indicator for water quality (see also chapter “use of plant protections products” and “fertilizer use”). Data on this indicator may be difficult to obtain at a global level, as maximum allowable levels are not harmonized worldwide and data may not be reliably collected or reported.

The main challenge with indicators of water quality is data availability (Hsu 2014).

Fertilizer use and plant protection product (PPP) use are to some extent exceptions, as more work has gone into developing datasets, models and indicators of their impact; their relevance and associated indicators are explained in the following subsections.

10.1.4 Climate

Relevance

Climate change is among the greatest environmental threats of humanity. Many studies have documented responses of ecosystems, plants and animals to the climate changes that have already occurred.

Global warming has many environmental impacts including:

- Changes in biodiversity, the timing of seasonal events and habitat use
- Changes in biodiversity distribution and abundance/composition of plant and animal communities
- Melting glacial ice: implications on the global freshwater resources’ in areas depending on glaciers

- Increased evaporation due to rising temperatures (e.g. resulting in droughts)
- Increased risk of extreme weather events

In its fifth assessment of the relevant scientific literature, the Intergovernmental Panel on Climate Change (IPCC) reported, that scientists consider it as "extremely likely" that human influence has been the dominant cause of the observed warming since the mid-20th century and evaluate the human influence on global warming as "extremely likely" (IPCC 2013).

Land use, land use change, and forestry (LULUCF) are major contributors to global greenhouse gas (GHG) emissions, responsible for about 30 % of global emissions, though estimations vary depending on definition and methodology (IPCC 2013).

Data requirements/measurement

Greenhouse Gas emissions from LULUCF are expressed in "**CO_2 Equivalent Emissions with Land Use, Land-Use Change and Forestry".** Accounting[37] CO_2 equivalent emissions goes beyond CO_2 emissions and include other GHGs such as ammonia, methane and nitrogen oxide.

However, carbon plays a particular role in terms of GHG emissions from land use, so that a carbon related indicator can provide relevant additional information. For example, the model developed by (Müller-Wenk and Brandao 2010) investigates the global warming potential of land use as part of the UNEP/SETAC Life Cycle Assessment . Their study focuses on the climatic impact of land use as determined by the CO_2 transfers between vegetation/soil and the atmosphere in the course of terrestrial release and re-storage of carbon. They analyse "**carbon transfers to the air per hectare**", as well as imputable durations of carbon stay in air. This indicator could be useful for quantifying both sink and source impacts of land use, i.e. GHG storage or emission capacity. However, the categories developed for land use are not product or crop type-specific.

10.2 Land Use Indicators – Overview

The most important direct drivers of biodiversity loss and ecosystem service changes are habitat change (such as land use changes and water withdrawal from rivers with regard to terrestic ecosystems), climate change, invasive alien species, overexploitation, and pollution (Millennium Ecosystem Assessment 2005). Habitat change both due to land conversion and non-sustainable land use management therefore constitutes an important impact category.

There are two general distinctions of impact pathways of land use. They are termed differently in different studies, but essentially relate either to

1. land transformation (land conversions/changes in land use) and/or
2. land occupation and land management including land use intensity.

Both categories are drivers of environmental change as shown in Figure 11 (Hauschild et al. 2011).

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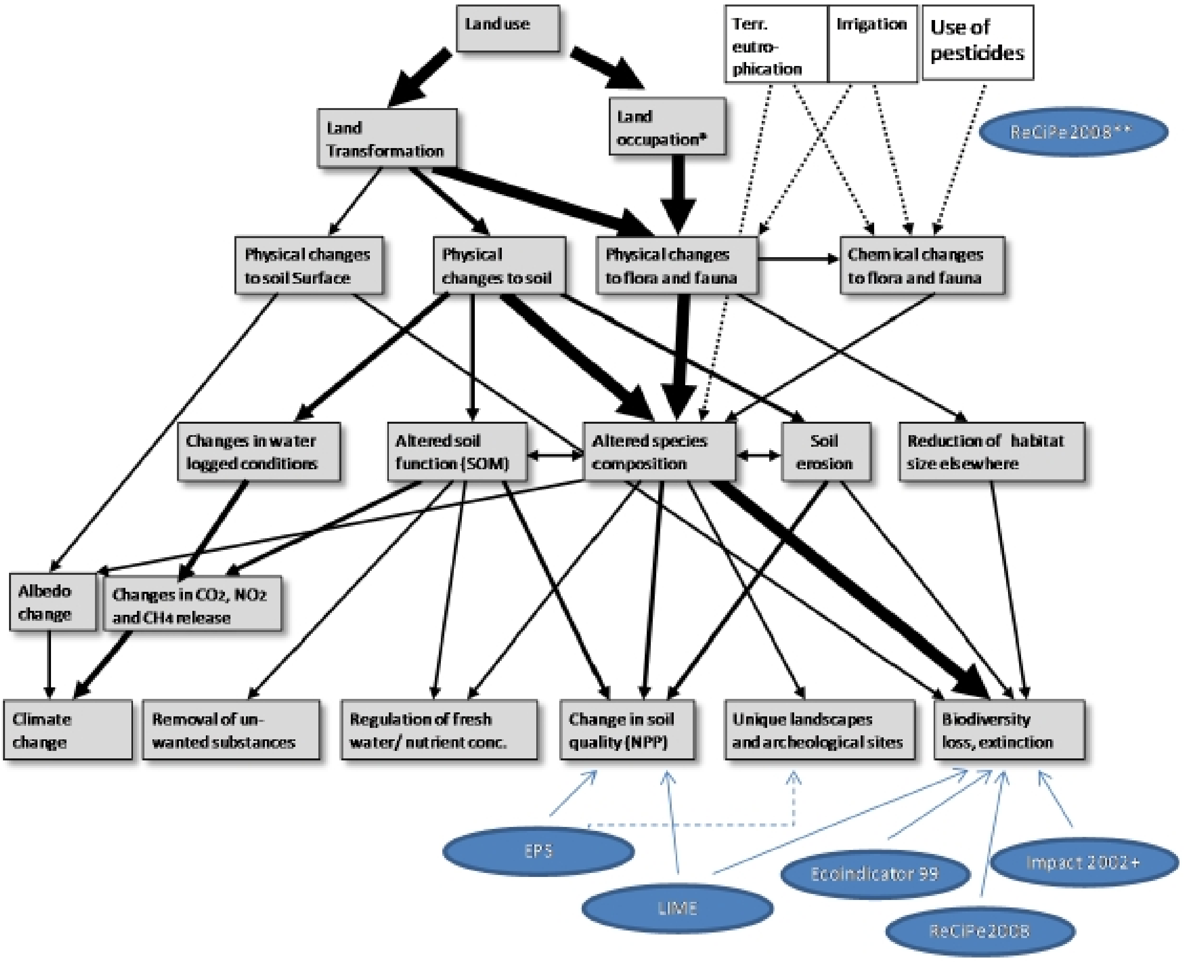
[37] There is a growing emphasis on accounting of imported and exported emissions and carbon leakage. This approach argues that countries should be responsible for emissions from the production of products imported from other countries, and that emission reduction requirements and calculations should take these imported emissions into account to prevent leakage and accurately represents the emissions impact of a country's consumption.

Figure 11: Impact pathways of land use according to Hauschild et al. 2011



10.3 Land use intensity

10.3.1 Input intensity

10.3.1.1 Fertilizer use

Relevance

The use of mineral and organic fertilizers in agriculture is an important tool to increase crop output. However, fertilizer (over)use leads to significant environmental hazards, such as water, air, and soil pollution, and has negative effects on other environmental components. Fertilizer use interferes for example with the natural balance of microflora in soil and water(European Environment Agency 2009). It also has negative impacts on biodiversity, from microbes to large fauna.

Fertilizer overuse can also have a major impact on water quality. High levels of nitrate and nitrite in drinking water are a hazard to human and environmental health, as are increased levels of ammonia (NH_3) and NO_x as contributors to acid rain, particulate matter and ozone. The runoff of excess fertilizer into water sources has led to eutrophication and hypoxia in fresh and salt waters across the globe, including massive “dead zones” where fish and plant species cannot survive, leading to the collapse of marine and aquatic ecosystems and fisheries. Nitrogen fertilizer use also contributes significantly to greenhouse gas emissions – nearly 60% of N_2O emissions globally stem from agriculture (IPCC

2007). World phosphorous reserves are also dwindling, meaning that the possibility for endless use of mineral fertilizers is limited (Gilbert 2009).

Data requirement/measurement

Fertilizer use expressed as „**Total fertilizer use per ha**" is a proxy indicator for land use intensity. Fertilizer use refers to organic and mineral fertilizer, the latter of which consists of nitrogen (N), phosphate (P_2O_5), and potash (K_2O) fertilizers. Depending on the data set used, these can be disaggregated, nitrogen being the fertilizer most relevant for negative impacts.

Though measuring fertilizer application rates does not give a clear 1:1 indication of the environmental impacts and largely depends on use patterns and external factors (such as pollution abatement methods, soil and plant types, and meteorological conditions), monitoring fertilizer application can help evaluate risks of environmental and human health damage.

An alternative indicator that provides better information about the potential overuse of fertilizers is the "**nitrate or chemical content of (ground) water**". High nitrate concentration in water can affect its potability and is a result of leaching from fertilized soils.

For grassland when fertilizer application is unknown, the **stocking density** of cattle can be used as a proxy (Kuemmerle et al. 2012). Current data on fertilizer consumption are available for many countries through FAOSTAT (FAOSTAT 2013b), however current data on fertilizer application per crop type are less readily available, as this is not regularly measured (FAO 2006).

Going beyond fertilizer application rates, the **nutrient balance** or nutrient budget approach can be another way to monitor fertilizer (over)use. It measures the **total input of nutrients compared to the total output for a given area** of land (Eurostat and OECD 2013). Since this method measures the total input of nutrients, it does not only account for fertilizer but for all nutrient sources, including biological nitrogen fixation and, in some models, seed material itself.

By shifting the focus to nutrient surplus, i.e. nutrients that are introduced to the soil but not used by crops, this method can serve as a better indication of excessive or unnecessary use of fertilizer and associated environmental and health risks. The measurement of nutrient surplus (especially **nitrogen surplus**) is an accepted measure for the efficiency and sustainability of fertilizer use. It is used for example by the OECD as an agri-environmental indicator, for which there is reliable data in OECD countries (Parris 1998; OECD 2013), and the FAO (OECD and FAO 2012).

10.3.1.2 Use of plant protection products

Relevance

Plant protection products (PPP) are important tools for increasing crop yields. PPP include pesticides (insecticides, acaricides, etc.), herbicides and fungicides. Their (over)use can lead to negative environmental and health impacts, and increasing use of PPP (even within recommended dosages) does not necessarily decrease crop losses over time (Pimentel 2005).

PPP have a negative impact on biodiversity and ecosystems services. Decreases in pollinators such as (wild) bees and insects due to pesticide use poses a particularly serious threat to human well-being, as much of agricultural productivity and many natural ecosystems are dependent on pollinators. The total economic value of pollination is estimated at over €150 billion annually (Pimentel 2005). PPP in water supplies poses a major human and environmental health risk. PPP from direct application and from runoff pollute surface and ground waters as well as soils, reducing water potability and reducing biomass and species diversity of flora and fauna. Fish, amphibians, birds, and invertebrates are particularly at risk.

Acute exposure can lead to poisoning illness and death. Long-term exposure can lead to health risks such as cancer and neurological, respiratory, and reproductive problems (Pimentel 2005). Some PPP compounds are very persistent in the environment; it is these that often pose the largest risk to human and environmental health (FAO and WHO 2014).

There are guidelines for their safe use, but these guidelines are often not rigorously implemented, leading to higher risks for humans and the environment. This can be especially the case in developing countries where oversight can be minimal to non-existent and farmer and where farm worker education levels are low. PPP residues are common in consumer food products (Pimentel 2005) as well as in human urine (Friends of the Earth Europe 2013), the precise health risks of which at low and high levels are unknown.

Data requirement/measurement

As with fertilizer use, there is no universal or absolute relationship between pesticide use and environmental or health damage, but indicators for pesticide use intensity can aid in risk evaluation (Eurostat 2008). Different measurements can be used as indicators for PPP use. Most measurements **cover overall PPP use or PPP use per unit of land** rather than use per crop. The FAO collects statistics on PPP use on crops and seeds, broken down into different categories based on the type of PPP, but does not collect data on PPP use per crop. The data is also reported non-uniformly across countries, with countries reporting "use" as either formulated product, sales, distribution or imports for use in the agricultural sector; however the FAO present statistics in standardized measurements (FAOSTAT 2013a).

Schönthaler and Pieck (2013) suggest using the indicators total pesticide use and/or a measurement of PPP use intensity, i.e. the **amount of pesticide used compared to maximum recommended or allowed levels**. This indicator more directly represents the appropriateness of use or the overuse of PPP. However, recommendations or maximum allowed amounts are not uniform across countries, regions, ecosystems, or time.

Levels of PPP in (ground) water can be another indicator for environmental impact of pesticides. Again, as with other water quality indicators, uniform and reliable data collection is a challenge.

The OECD developed a set of indicators for sustainable PPP use and environmental risk of PPP use. The indicators are separated into a suite of **Aquatic Risk Indicators** and **Terrestrial Risk Indicators** (OECD 2014). Originally developed in 2002, the indicators are currently under review, taking into account the Harmonized Environmental Indicators for pesticide Risk (HAIR) developed for the EU, which consist of 31 absolute exposure and risk indicators also including Occupational Risk Indicators (Kruijne 2012). Both the OECD indicators and the HAIR indicators are composite indicators representing the environmental impacts of PPP use and were chosen based on their robustness, user friendliness, and data availability.

10.3.1.3 Irrigation use

Relevance

Water is a renewable resource insofar as consumption rates do not exceed replenishment rates. Many water resources are overexploited, especially groundwater and transboundary watersheds (FAO 2011). Increasing water scarcity worldwide is putting stress on irrigated production. Especially in areas of rapid population growth and in key cereal-producing areas, surface and ground water supply is being outstripped by demand and conflicts between sectors and user groups have arisen (FAO 2011). Long-term improper irrigation techniques can cause salinisation and soil degradation.

Data requirement/measurement

As a proxy the "**share of irrigated land in total cropland**" can be used, as used e.g. within the EU research project VOLANTE (VOLANTE project 2012). However, the link to sustainability may be different depending on water availability, country, and time frame, and a model remains to be developed to break this down by crop. Information is collected based on existing geographical databases. FAOSTAT also collects data on irrigation and water use.

10.3.2 Management practices

Indicators to assess the environmental impacts of land management practices are different for the different land use sectors. The following subchapters list indicators for cropland, grassland and forestry management.

10.3.2.1 Agro-diversity

Indicators for sustainable crop production and agrodiversity can either relate to the basic characteristics such as **field size** and **crop diversity** and cropping intensity (**crop rotation and frequency**). Crop rotations and the frequency of cropping are important indicators to assess the intensity of cropland management. It can be measured by separating single cropping and multi-cropping areas, e.g. on an annual basis. The indicator cropping intensity (rotation and frequency) has been used within the EU research project VOLANTE project as part of an indicator set for land use change and land use intensity (VOLANTE project 2012). Also, Fehrenbach (2014) uses crop rotations to assess "Hemeroby" (see Annex I) by describing different crop rotations and compositions.

"Field size" is another indicator used within the EU VOLANTE project (VOLANTE project 2012; Fehrenbach 2014). Agricultural field size is related to a range of indicators capturing aspects such as the likely degree of degree of mechanization and landscape diversity/biodiversity. Within the VOLANTE project four classes are distinguished (< 0.5 ha, between 0.5 and 1 ha, between 1 and 10 ha and equal to or larger than 10 ha), while Fehrenbach (2014) differentiates 5 classes under the category "size of cuts" ranging from no mono-structured cuts (e.g. agro-forestry) to average cut size above 2.5 hectares. Proxies for agro-diversity also include proxies such as "**number of weed species in the cultivation area**" (Fehrenbach 2014).

Other indicators focus on land use classifications with certain management requirements as a proxy. This includes "**area under sustainable land management**" or **"% of cropland under organic farming**", "**area under agri-environment payments**" etc. These indicators are essentially composite indicators as they define categories that have several management requirements. Due to different definitions, these requirements may be difficult to compare on a global level.

10.3.2.2 Grassland management

Indicators on the grazing intensity assess the environmental impact of livestock. One way is to assess "Stocking density" that can be measured as **livestock units/animal units per hectare**.

Another indicator is "**Grassland Management frequency**". This indicator provides information on whether grassland areas are managed (i.e. cutting) and whether this management is taking place once or multiple times throughout a year. This indicator was used within the VOLANTE project and differentiated three categories: no cutting, single, or multiple cutting events (VOLANTE project 2012).

However, data on grazing intensity or feed production are unavailable at the global scale, or they are associated with large uncertainties in specific regions (e.g. Africa) (Vaclavík, T. et al. 2013).

While indicators of livestock densities and major livestock products (meat, milk, eggs) exist, considerable gaps relate to the extent of grazing land and the amount and types of biomass grazed. Likewise, infor- mation on other input indicators is missing, particularly regarding the spatial pattern of feed and forage production and consumption, fertilizer applied to pastures and grassland drainage (Kuemmerle et al. 2013).

10.3.2.3 Forest Management

For forest areas, indicators like i) basic information on **forestry management systems** (e.g. close-to-nature, intensive plantations etc.) as used within the EU research project VOLANTE; ii) **harvest practices** (e.g. % clear-cut harvest); and iii) **content of deadwood in forests** (as an indicator for biodiversity and management intensity), can indicate the intensity of forest management practices.

Within the VOLANTE project a combined indicator "**forest harvesting intensity**" was used that combines remote sensing indicators and forest harvesting statistics (from 2000 – 2010) to provide a map of forest harvesting intensity (VOLANTE project 2012).

Compared to the relatively rich data availability regarding cropland use intensity, data gaps appear large regarding global forestry intensity, for which major advances could be made from maps of broad types of forestry systems (e.g. plantations, agroforestry, managed and unmanaged natural forests, as well as forest harvesting) (Kuemmerle et al. 2013).

10.3.3 System indicators

Similarly to indicators that provide information about inputs metrics (fertilizer, plant protection products etc.), there are others that provide information about the output of certain land use activities (crop yields, wood fellings etc.). However, input and output data on yields alone are difficult as an evaluation basis for environmental impacts. While single metrics on input and output are relatively easy to compute and interpret, they do not provide a coherent picture of intensification as a) yields are not yet set into relation of the bioproductivity of the land and b) give no information about impacts of land use management practices (e.g. human factors and technology). On the other hand indicators on bioproductivity/biotic production potential of a piece of land alone do not reflect which link exists to the actual production. Similarly, indicators that focus only on land use intensity, such as cropping intensity, grassland management frequency, grazing intensity[38] or fertilizer use are valuable, but lack information about production efficiency.

It can therefore be valuable to connect potential and actual productivity indicators as done within system indicators.

System Indicators give information about aggregated effects of land use intensity. They relate the inputs or outputs of land- based production to system properties e.g. yield gaps (actual versus potential yield), human appropriation of net primary production (HANPP), or wood to wood increment ratios. This group of land use intensity indicators relies on a reference value and combines measurements, either from satellites or on the ground, with model outputs (Kuemmerle et al. 2013).

Limitations towards system indicators however remain as higher intensification rates do not always lead to higher production and high production is not necessarily achieved in a sustainable way so that complementary indicators are necessary to achieve meaningful evaluations.

10.3.3.1 HANPP

HANPP, the "**human appropriation of net primary production**" is an aggregated indicator that reflects the impact of land use on biomass available each year in ecosystems.

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[38] The three indicators are suggested within the VOLANTE project: Cropping intensity is measured in "cropping intensity (single vs. multiple cropping) in cropland based on MODIS satellite image analyses from 2000-2011", Grassland management frequency is measured as "Management frequency (cutting) on grasslands based on MODIS satellite image analyses from 2000-2011", grazing pressure maps derived via disaggregating livestock statistics from 2000-2011 (stocking rates).

More specifically, NPP (net primary production) is the net amount of biomass produced each year by plants; it is a major indicator for trophic energy flows in ecosystems. HANPP measures to what extent land conversion/land use change and biomass harvest (or burning) alter the availability of NPP (biomass) in ecosystems. It is a prominent measure of the "scale" of human activities compared to natural processes. (Haberl, Erb, and Krausmann 2013)

HANPP is calculated as the difference between the NPP of potential vegetation (NPP_0), i.e., the plant cover that would prevail in the absence of human intervention, and the fraction of NPP remaining in ecosystems after harvest (NPP_t). NPP_t is calculated by subtracting the amount of NPP harvested or destroyed during harvest (NPP_h) from the NPP of currently prevailing vegetation (NPP_{act}). HANPP, thus, is the sum of NPP_{LC} and NPP_h, where NPP_{LC} denotes the impact on NPP of human-induced land conversions, such as land cover change, land use change, and soil degradation (Haberl et al. 2007). Hence, land use sometimes reduces NPP, even prevents it altogether (e.g. soil sealing), but technologies such as irrigation, fertilization or use of improved crop varieties may also raise NPP over its natural potential (Haberl, Erb, and Krausmann 2013).

HANPP can be expressed as material flow (kg dry matter biomass), as a substance flow (kg carbon) or as an energy flow (Joule). Also, HANPP can be presented as a percentage of potential NPP (Haberl, Erb, and Krausmann 2013). Calculations are made based on FAO country-level land use, harvest, livestock, and fire data.

Species richness and flows of water, carbon, and energy as well as ecosystem service provision have been shown to be related to HANPP, so HANPP indicators can also be extrapolated to provide information for analysis of these factors (Haberl et al. 2007).

However, a certain HANPP value does not necessarily equate sustainable use, as it does not take negative impacts of intensification into account, i.e. effects of pollution, water imports, etc.

Therefore, an evaluation of HANPP – in this case in the context of the land footprint methodology – is not straight forward, as (further) increases in HANPP can have possible adverse ecological effects. Land-use induced changes in productivity may also affect many important ecosystem services such as the resilience, buffering capacity or the absorption capacity for wastes and emissions (Haberl, Erb, and Krausmann 2013). Moreover, long-term studies of HANPP have shown that HANPP may decline during industrialization if biomass harvest grows due to agricultural intensification (Haberl, Erb, and Krausmann 2013). HANPP can therefore not be used as a standalone indicator for productivity but needs to be accompanied with indicators that assess sustainability of practices.

Difficulties to use the HANPP concept can also arise due to the different definitions used and a lack of standardization that has resulted in a range of empirical results (Haberl, Erb, and Krausmann 2013). Haberl, Erb, and Krausmann (2013) therefore consider harmonization of HANPP definitions as crucial.

10.3.3.2 Yield gaps

Yield and production gaps are estimated by comparing potential attainable yields and production (e.g. through econometric modelling) with actual achieved yields and production for main commodities. They can be measured as "**ratio of actual vs. potential yields**". Global information on yield gaps is accessible through e.g. the Global Agro-Ecological Zones (GAEZ) methodology, developed by the (FAO) and the International Institute for Applied Systems Analysis (IIASA) (FAO 2014a).

GAEZ results take into account rain-fed and irrigated water supply conditions and are calculated with potential yield and production for assumed low and mixed level of inputs and management circumstances.

Dietrich et al. (2012) presents a slightly different approach: a measure, called the **τ-factor**, that is presented as an alternative to current measures for agricultural land use intensity and its expression through yield gap analysis.

Yield gap analyses assume that each location has an upper yield boundary, called either "potential yield" or "technology frontier", which is determined by present physical conditions and available technologies.

The concept of agricultural land-use intensity as expressed in the τ-factor does not measure the distance to a technology frontier or potential yield. Instead, it is a productivity measure which takes only the **human-induced productivity** into account, explicitly including those that affect the technology frontier like the development of new varieties.

More specifically, the τ-factor is the **ratio between actual yield and a reference yield under well-defined management and technology conditions**. By taking this ratio, the physical component (soils, climate), which is equal in both terms, is removed. Instead, it is a productivity measure which takes only the human-induced productivity into account.

Although both measures can be calculated in similar ways, their meaning is different: yield gaps measure the distance to the current best practice, typically excluding possible changes in best practices, whereas land-use intensity measures all those parts of agricultural productivity, which cannot be explained by the physical environment (soils, climate).

Dietrich et al. (2012) acknowledge that yield gap analysis is a very powerful tool when it comes to comparing the current productivity levels. However, when it comes to the analysis of land use intensities in larger spatial or temporal domains (where potential yields are bound to change and very heterogeneous environmental conditions have to be considered), the yield gap analysis is less suitable than τ. The following example that focuses on technology changes over time illustrates this and also shows the shortcomings of yield gaps as a surrogate for land-use intensity (low yield gap ⇢ high land use intensity, high yield gap ⇢ low land use intensity):

When technological change takes place over time (e.g. newly bred varieties) but is not being adopted (assuming constant environmental conditions) the measure for land use intensity τ is unaffected: The actual yield does not change as well as the reference yield does not change and τ reports constant land use intensity. The yield gap analysis on the contrary shows an increasing yield gap, as the potential yield increases but the actual yield remains unchanged. Interpreted as land use intensity that would lead to the wrong conclusion that intensity decreases, even though production methods remain unchanged (Dietrich et al. 2012).

10.3.4 Bio-productivity weighted land footprint

A bio-productivity weighted land footprint provides an indicator for a basic provisioning service of ecosystems, namely biomass productivity. The amount of biomass supplied by a hectare of land differs significantly across land use types and ecosystems.

Bio-productivity indicators have been discussed as productivity-weighted land footprints, building on the assumption that different land types and land uses deliver different ecosystem services; in particular they have different bio-productivity, i.e. biomass productivity depending on biophysical endowment. To develop a productivity weighted land footprint, a productivity weighted area is normalized to the area-weighted average productivity of biologically productive land (see Ewing et al. 2012; Weinzettel et al. 2013).

The bio-productivity footprint thereby brings the land footprint, which describes extents of land areas used for consumption (calculated in AP1 of this study), to a common reference level and allows for better country-by-country comparisons than the "actual hectares" reported in land footprints.

This is in particular relevant for ecosystems with widely varying quality and biomass productivity. For example global grassland areas cover about 3400 million hectares. Comparing potential grassland productivity data with a reference yield of five tons consumable biomass per hectare per year (as e.g. achieved on medium to highly productive grassland in Northern Europe), suggests that instead of 3400 million hectares of grassland, only an equivalent 1400 million 'reference' grassland is globally available. The former number would represent a "actual hectares" land footprint, while the latter refers to a "bio-productivity" footprint.

Another example are extensively used arid areas representing a large share in the land footprint of many countries. Depending on the land flow accounting methodology this may result in extremely high land footprints (of actual hectares used) for countries such as Mongolia or Australia. In contrast the "bio-productivity footprint" per citizen of these countries is comparable or even below the one of EU citizens.

The most standardized approach currently available to calculate this indicator is the concept of Human Appropriation of Net Primary Production (HANPP) (see separate chapter on HANPP). $NPP_{harvest}$, one of the HANPP indicators, measures the harvested amount of carbon and is a territorial (production-based) indicator. In combination with global biomass or land flow accounts, it can be calculated as a consumption-based (footprint-type) indicator, i.e. calculating the embodied $NPP_{harvest}$ (measured in carbon content) in consumption.

For this required data includes:

- Material flow accounts (taken from harvest and trade statistics, supply utilization accounts)
- Information on the carbon content of different crops (taken from IPCC, FAO)

An alternative approach to calculate the appropriated bio-productivity is to normalise the land footprint, e.g. according to global average yields. This concept is used for the calculation of the ecological footprint, where different land use types are weighted using 'yield factors' and 'equivalence factors' in order to aggregate all land use into a common unit of "global hectares", i.e. hectares with average global productivity. The yield factor quantifies to what extent a countries' productivity of e.g. a certain agricultural crop differs from the global average yield of that crop, while the equivalence factor weights the various land use types against each other, e.g. taking into account that agricultural areas in general are more productive compared to pasture land. This approach is contested scientifically for its large number of underlying assumptions. However, it has the advantage to offer clear and simple results expressed in hectares, which makes the planetary boundaries more tangible than for indicators measured in tonnes.

Required data includes:

- Material or land flow accounts (harvest and trade statistics, supply utilization accounts)
- Normalization factors (country-specific measures for the bio-productivity of different agricultural and forestry areas; global average bio-productivity)

Data availability:

- Bio-productivity measures for cropland can be based on global yield information from FAOSTAT.
- For grassland and forests, global biogeographical models such as GAEZ (Global Agro-Ecological Zoning, IIASA/FAO 2012) can provide the required information.

Embodied $NPP_{harvest}$ and the normalised land footprint can be very useful to monitor the appropriation of the bio-productive capacity of ecosystems, a truly limited and valuable resource.

10.4 Land conversion

Land use change is major driver of land degradation, greenhouse gas emissions (e.g. through deforestation, drainage of peatlands etc.) and biodiversity loss (conversion of natural land/grassland into arable land etc.).

The damages of land use change are largest for land use types which are difficult to restore and need extremely long to develop, e.g. thousands of years and more for primary forest and peatbog (Koellner and Scholz 2008).

Environmental impacts due to **indirect land use change (ILUC)** have been out of the scope of this project due to many reasons. One main reason is the methodological uncertainty around it. However, if to be included in a land footprint approach the efforts of bioenergy policies to include ILUC effects particular with regard to greenhouse gas emissions in biofuel sustainability standards and efforts to define ILUC default values for different biofuel sources and regions can provide a starting point. (e.g. in US and EU policies). For example the California Air Resources Board (CARB) approved specific rules and carbon intensity reference values including ILUC for the California Low-Carbon Fuel Standard (LCFS).

10.4.1 Conversion to/from forest land (deforestation/afforestation)

Relevance

Forests play a crucial role in climate change mitigation and in the conservation of biodiversity as well as of soil and water resources. Deforestation results into habitat and biodiversity loss and aridity. It has adverse impacts on bio-sequestration of atmospheric carbon dioxide. Deforested regions typically show high levels of soil degradation and erosion with a high potential to become wasteland in the mid term.

Data requirement/measurement

The conversion to or from forest land can be measured as **“Rate of conversion of forest area/clearing of native forests compared with the agreed reference level”** (**gross deforestation**).

Also, increases in the establishment of new forests (“**afforestation and reforestation**”) can be an valid indicator, but should not be equally counted to forest areas and taken from the gross deforestation figures (expressed as “net deforestation”), considering the different quality of forests (the carbon losses and massive changes in biodiversity) if native forests are cleared.

With regard to the project approach to link impact oriented indicators to production a deforestation indicator seems particularly promising, as recent research efforts have shown that with the data and models available a link can be drawn. Within the study “The impact of EU consumption on deforestation” the concept of the single indicator “embodied deforestation” was developed to represent “the deforestation associated with the production of a good or commodity... to link deforestation in producer countries/regions with the associated consumption of goods in consumer countries/regions” (European Commission 2013). “Embodied deforestation” refers to the deforestation embodied (as an externality) in a produced, traded, or consumed product, good, commodity or service (European Commission 2013). The study showed that the EU 27 imported and consumed 36 % of all crops and livestock products traded at the global market, which are associated with deforestation in the countries of origin. Thus, the EU has imported and consumed a deforested land area of 9 million ha over the period 1990 – 2008 (European Commission 2013). The analyses undertaken in this study are based on two models combining and comparing physical with monetary-based data sets:

- LANDFLOW, a physical units-based trade model, which can track the trade of agricultural and forestry commodities and their embodied deforestation between countries based on FAO time-series harmonized databases covering the period 1990 to 2009.
- GTAP-MRIO, a monetary-based model to simulate how all products derived from agricultural and forestry commodities are traded throughout the world. The model can trace the embodied deforestation up to the final consumer sector in a country or region.

With FAO data, the LANDFLOW model builds on the most comprehensive data base on deforestation and forested land at global scale, while delays and gaps in data still occur (European Commission 2013). However, it has to be noted that 25 % of deforestation remains unexplained and forest degradation was not quantified in the study. Hence, no conclusions on forest management practices, which seems crucial for a further qualification of the land footprint indicator can be drawn from the approach chosen in European Commission (2013a).

Similar to Lenzen et al. (2012) for biodiversity, Meyfroidt, Rudel, and Lambin (2010) directly linked deforestation to global trade. In fact, the study tested whether there is an association over time between a reversal in national deforestation trends and an increase in net imports of wood or agricultural products. Based on data on de- and reforestation as well as on national imports of agricultural commodities from FAOSTAT and United Nations COMTRADE data, a net displacement of land-use demands via international trade was calculated. The results show that most countries that experienced a forest transition (reducing deforestation rates or increasing reforestation) increased their net displacement of land demand through imports of agricultural commodities at the same time.

10.4.2 Conversion to/from cropland & change in grassland area

Land-based agricultural production is expected to increase further to meet future demands for food and other commodities, such as biofuel or fibre. However, as fertile land resources are getting scarcer and ecosystem functions and services degraded, there is only little room for agricultural expansion.

Indicators on **cropland expansion** and **changes in grassland areas** can therefore provide valuable information. In addition it might be useful, to also see developments outside the primary sectors, i.e. the “**change in non-arable land use**” (e.g. marginal land uses).

10.4.3 Land restoration

The restoration of an area is eventually a change of land use, which has usually positive environmental effects. However, restored areas are different to quantify given the different and often wide ranging temporal dimension of restoration (e.g. regrowth of primary forests and peatland) and globally comparable data may be difficult to obtain. A proxy for land restoration can be the area classified as “**area restored**” within a country or region.

10.4.4 Land take/sealing

Land take is understood as ”urbanisation” or ”**increase of artificial surfaces**” and represents an increase of settlement areas or artificial surfaces (including urban development for housing, services or recreation, and industrial, commercial and transport networks and infrastructure) over time, usually at the expanse of rural and natural areas (European Commission 2012b).

Land take often results into soil sealing (e.g. from infrastructure, settlement, transport networks etc.). Other environmental impacts of land take include **“habitat fragmentation”**, an indicator that is further discussed in the biodiversity section of this report. Land take can be measured in **hectare per year**. The **reduction of land take rates**[39] is an important political goal of the EU Roadmap to a Resource Efficient Europe (COM (2011) 571) and a key indicator of Germanys “Federal Strategy for Sustainable Development”[40] that is in place since 2002.

Not included in land take statistics, but a potentially relevant indicator for land conversions beyond the primary sectors (forest, grassland, cropland) and land take for urbanization can be the **share and development in the size of mining areas**.

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[39] land take owing to human activity, in particular urban development for housing, services or recreation, and industrial, commercial and transport networks and infrastructure.

[40] Since 2002 the Federal Government of Germany has a “30 hectare goal” by 2020, meaning that the land take in Germany should be reduced to 30 ha per day by 2020. The “30 hectare goal” is a non-binding political intention, as laid down in the Federal Strategy for Sustainable Development, that defines the increase/decrease of the settlement area per day as one of 21 sustainability indicators.

11 Annex 3: International Expert Workshop

On June 25th 2014, a group of international experts met at the Umweltbundesamt (Berlin, Bismarkplatz 1) for the workshop "**Improvement of the land footprint methodology through impact oriented land use indicators**" to discuss intermediate results and guide on further research.

11.1 List of participants

First name	Last name	Organisation
Rolf	Bräuer	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB)
Martin	Bruckner	Vienna University of Economics and Business
Jacques	Delsalle	European Commission, DG ENV, B.1
Knut	Ehlers	The Federal Environment Agency
Horst	Fehrenbach	Institute for Energy and Environmental Research
Günther	Fischer	International Institute for Applied Systems Analysis
Stefan	Giljum	Vienna University of Economics and Business
Michael	Golde	German Environment Agency (Umweltbundesamt UBA)
Klaus	Hennenberg	Oeko-Institut
Frank	Hönerbach	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB)
Almut	Jering	German Environment Agency (Umweltbundesamt UBA)
Timo	Kaphengst	Ecologic Institute
Clunie	Keenleyside	Institute for European Environmental Policy
Thomas	Köllner	University of Bayreuth
Cathy	Maguire	The European Environment Agency (EEA)
Ines	Martins	German Centre or Integrative Biodiversity Research (idiv)
Helmut	Mayer	Federal Statistical Office Germany (Statistisches Bundesamt)
Nicolas	Merky	Federal Office for the Environment Switzerland
Meghan	O´Brien	Wuppertal Institute
Gertrude	Penn-Bressel	German Environment Agency (Umweltbundesamt UBA)
Gundula	Prokop	Environment Agency Austria
Ariadna	Rodrigo	Friends of the Earth Europe
Agnieszka	Romanowicz	Joint Research Centre
Sylvia	Schwermer	German Environment Agency (Umweltbundesamt UBA)
Stephan	Timme	German Environment Agency (Umweltbundesamt UBA)
Sylvia	Tramberend	International Institute for Applied Systems Analysis
Jan	Weinzettel	The Charles University Environment Center
Stephanie	Wunder	Ecologic Institute

11.2 Agenda

Time	Item	Input
10:00 – 10:30	Registration and Coffee	
10:30 – 10:45	Welcome and Introduction	UBA
10.45 – 11.00	Brief introduction round	All
11:00 – 11:30	Options for further development and standardization of the land footprint methodology	Martin Bruckner
11.30 – 11.45	Responses: Helmut Meyer, German Federal Statistical Office Meghan O'Brien, Wuppertal Institute	
11.45 – 12:15	Discussion	Moderation: Stefan Giljum
12.15 – 13:15	Lunch	
13:15 – 13.45	Environmental impact indicators to further develop the land footprint methodology	Stephanie Wunder Günther Fischer Sylvia Tramberend
13.45 – 14.05	Responses: Nicolas Merky, BAFU Jacques Delsalle, EC DG Env	Moderation: Timo Kaphengst
14.05 – 15.05	Discussion (esp. along tables 1-3 of the report)	
15:05 – 15.20	Coffee break	
15.20 – 16.20	World Café – 3 tables on indicator categories: Environmental impact, Land Use Intensity and Land Use Change	Moderation: Ecologic Institute, WU, IIASA
16:20 – 16.50	Report back from the working tables and discussion	
16.50 – 17.00	Outlook and closing words	Stefan Giljum

11.3 Minutes of the meeting

Morning session

Reflections on work package 1 – land footprint calculations

After M. Bruckner introduced work package 1 and presented main results (presentation 1) H. Mayer and M. O'Brien commented on the accompanying report: Review of land flow accounting methodologies and recommendations for further development.

Response - Helmut Mayer (Federal Statistical Office)

Mr Mayer noted that he presents his subjective views and not those of the Federal statistical office.

He fully agrees on the assessment of the advantages of physical accounting for the following reasons: mass allocation (and not monetary accounting); high product detail; more transparency of the calculations, allows specification of use categories (food, feed, other uses)

He only partly agrees on the key disadvantages of physical accounting: i) data intensive, yes, but detailed base data are available (and monetary models may be even more data intensive); ii) also compare to MIOT (monetary input-output tables), which are also data intensive, i.e. both physical accounting and MIOT have a similar level of data intensity; iii) the stated "huge efforts for higher processed products" are manageable (again efforts for MIOT not smaller);

He states that the consideration of re-exports (and regional supply chains) is a real problem and requires considerable efforts for analysis.

There is limited availability of land use (intensity) coefficients for more complex/processed products. However, solutions to close the gaps for data availability exist (e.g. through life cycle assessment data).

A challenge for all methods lies in the calculation of import shares of exports; the import-content of exports is currently underestimated in many studies.

Mr. Mayer shares his view of the necessity and the advantages of using a global approach for land flow accounting. His view is that a national approach is feasible when only one country is considered. However, whether a global or national approach is used depends on the purpose of the study. National approach allows the use of trusted and higher detailed national statistics and uses only import data (for the study country). Export data are not necessarily required. Global approach uses global statistics and could lead to a propagation of potential errors in these data sources.

National technology coefficients are not necessarily important when calculating impacts for some products (e.g. oil mill technology is similar globally). However, animal product technology differences are a problem, when only using domestic technology, as livestock production systems differ across countries. What is equally or more important is the use of detailed import statistics.

Response - Meghan O'Brien (Wuppertal Institute)

Meghan O'Brien presents on both comments of Helmut Schütz and herself. Mr Schütz will send additional comments by email.

General congratulations on the report. She mentions explicitly the usefulness of the overview and timeline of different land flow accounting approaches (see Fig. 2 in the workshop paper on land flow accounting methods).

She fully agrees with the recommendation to calculate separate land footprints for cropland, grassland, forest land because of different impacts. Concerning the latter two she even asks whether land footprint are really the best approach for describing resource use of grassland and forests. Instead of a land footprint in hectares, the used physical volumes should be measured. E.g. for pasture the land footprint would depend largely on intensive/extensive systems, hence there are difficulties to interpret policy implications. It may be more useful to compare meat consumption rather than pasture use for policy. For forest land usage cycles are much longer than cropping cycles, hence they are difficult to capture by annual statistics. It may be better to link to forest product usage volumes rather than land use for comparison to crops. Wuppertal Institute combines harvested timber volumes with net annual increments to estimate the theoretical forest area required by wood consumption. However non-wood products may still be an issue.

She also acknowledges the difficulty in accounting for processed products and states the need to have reference values for sustainability assessments. Trends towards a bio-economy and innovative products will make land use accounting even more challenging. She considers it important to include a discussion on how to anticipate and monitor future challenges for land footprint accounting, such as the correct consideration of biomaterials.

She stresses that a policy perspective should be added to all methodology descriptions as was done e.g. on p.40 of the report. The key question is which policy questions can be best addressed using which type of methodology.

Referring to Mr. Mayer's comments she acknowledges some efforts required for the calculation of re-exports and multi-cropping and would welcome a procedure with a land use accounting task force.

The source of data for the expected global land clearance until 2050 (see presentation) should be checked again. The land report of the International Resource Panel uses different data.

Discussion points from participants (other than project members and respondents)

Jan Weinzettel: Referring to Mr. Mayer he questions the assumption that raw materials are not being exported from Germany. There is a need for global trade and production values to account for impacts.

Nicolas Merky: Agrees that national data may be more precise but is less comparable internationally. Still open question how to compare national data on international level while preserving precision.

Almut Jering: It's important to link the methodology with policy questions

Frank Hönerbach: Within the debate around SDGs, there is the request for one single number/ one single indicator: Do we have one?

Meghan O'Brien: There is a single number available: 0.2 hectare is the average cropland area available per person worldwide (assumes a halt of deforestation by 2020 and divides global cropland of 1.6 Gha by population).

Thomas Köllner (per video): Some product groups have very different environmental impacts. Data are missing, e.g. organic production not distinguished in FAOSTAT. It would be very helpful to have a comparison between organic and conventional food impacts, but this is also difficult to separate (e.g. organic milk production uses more land but has less biodiversity impact).

Sylvia Schwermer: Sees large value added in further development of land use indicator. Need to consider policy aspects / questions / purposes!

Afternoon session

Extending land footprints with quality and impact indicators

The afternoon started with a presentation of S.Wunder and S.Tramberend introducing the environmental impact indicators for extending land footprints with quality and impact indicators (see presentation 2 and 3).

The presentations were followed by approx. 20 minutes o direct questions and responses. Many responses addressed the question of the general need to extend the land footprint with impact oriented indicators and the question which end use/implementation is foreseen for the final output of the project and to link to which policy debates this should be linked.

Most participants acknowledged that there is a need for land footprints but wondered if there are other ways to report on land use impacts beyond the methodological inclusion of impact oriented indicators within the land footprint.

Response - Nicolas Merky (Federal Office of the Environment Switzerland)

Mr. Merky presented Switzerland's experience with consumption based indicators for all products and services (the presentation cannot yet be published). They also used biodiversity and land use data. He mentioned the need to be careful about selecting just a limited amount of indicators and to provide context information in case of difficult and complex indicators. Within the Swiss approach they went for a rather pragmatic selection of indicators. With regard to the project question he gave the feedback that it is both feasible to account for impact oriented indicators and politically needed as a basis for knowledge based decisions.

Response - Jacques Delsalle (DG-ENV)

He acknowledges the project work as being complementary to work in preparation for the forthcoming 'land communication'.

For both processes he recommends to agree on our objectives first, esp. policy objectives, and then define the indicators.

The first questions should be: Where is our demand for land unsustainable? Which policy problem should be addressed by the solution suggested? Where are the most sustainable pathways for certain products (e.g. biofuels)? With regard to the latter it may be good to consider if certification schemes can help.

An important aspect that needs to be taken into account for this are leakage effects (including effects around the loss of fertile area in the EU (e.g. through land take) and impacts beyond EU borders to balance the loss of production (e.g. when we lose 1 ha in the EU we need 10 ha outside). .

With regard to the project objectives and referring to the UBA funders he is still uncertain about the policy objectives of this project.

He mentions that there are regional differences for the relevance of many indicators (e.g. water scarcity), so there might be a need for region tailored impact indicators. He also points to the importance to consider land use efficiency – this can be done through yield gaps or bio-productivity indicators as suggested within the project. Another important open question is how to include indirect impacts of land use and land use change. He also noticed that the indicators suggested are partly related to impacts, others to pressures and drivers (DPSIR model). It might also be helpful to categorize first the major land use types that we focus on and then attribute suitable indicators.

He argues that whatever impact indicators are identified within this project he would strongly recommend not to merge different indicators within a composite indicator, but that it is of higher relevance to have some data on agreed indicators that can be used to increase awareness and "alert" policy makers. Parallel activities should be undertaken to actually reduce demand for certain products (meat etc.)

Discussion points from other participants (other than project members and respondents)

Horst Fehrenbach: proposes to focus on a 3 step approach for the project: First: Is it at all possible to extend the land footprint with impact oriented indicators? Second: What are possible options for a solution? Third: Is the approach suggested useful for policy decisions and can it be communicated?

Knut Ehlers: adding a qualitative dimension to the land footprint is very useful. Likes the selection of indicators, but misses the identification of priority areas (eutrophication etc.) – project should look in the demand and needs for indicators. We need a step before indicators – What are key problems (priority areas) in land use? – Define the need for certain indicators

Ariadna Rodrigo: Wants to speak against doubts around the suitability of the land footprint: If they help to tell a story to people then this can be a valuable stepping stone. "People are not stupid" and will understand the indicator, even if there are some complex methodologies behind it.

Cathy Maguire: There is a need for a limited set of indicators

Sylvia Schwermer: Her preference would be to have an assessment both on the quantitative impacts as well as on the qualitative impacts of land use. While it certainly won't be able to define thresholds that say if a land use is sustainable or not, we will need to find indicators that allow to assess if we are getting better with our policies that aim to address the problems around land use sustainability.

World Café

The world cafe was structured around the question "Which impact oriented indicators do you think are most suitable as key indicators/proxies to "extend" the land footprint? Please rank!". This question was discussed in each of the three indicator groups. Below is the summary of results for each group

Environmental impacts

Among the top indicators people suggested the following for further consideration:

- There was an agreement about the suitability of soil organic matter as a key impact indicator. However, there are major data constraints.
- Biodiversity is an important category, too: Here, no single indicator of particular relevance was identifies, data availability and the missing link to primary production might also be a crucial problem.
- Water: There are regional differences in what matters most (water scarcity/ water quality, pollution or nutrients. There was also the call that even if there is little data available for water quality and water quantity: both should be considered together.

Participants also made suggestions which indicators could be skipped in an effort of identifying key indicators:

- Soil contamination (no data, not even in the EU)
- Fragmentation: no link to primary production
- Protected areas (too different to compare, they are a response not an impact)
- Wind and water erosion: no (up-to-date) global data

A general discussion took place if some indicator categories should not be part of a potential "extension" of land footprint given that they are dealt with in other political processes (e.g. climate and biodiversity). However, most participants disagreed with this approach and called for the importance of these issues and that they cannot be excluded.

People also recommended additional issues to consider:

- Adding to livestock diversity, crop diversity (cultivated crops) could also be a relevant indicator
- Local climatic impacts of land use might be interesting in addition to global climatic impacts
- In parallel to land footprints other footprint indicators could be used in parallel (carbon footprint, water footprint etc.), without even merging these approaches into one indicator. There is no need "to reinvent the wheel"

Finally some called for the „selection" of indicators, even if there are considerable data gaps. The communication of the importance of the indicator may lead to a better foundation of the data basis in the medium and long run and should not be neglected.

Land use intensity

- System indicators are useful and should be considered
- Within the category "Land Use Intensity" the proxy "energy use in agriculture" covers many issues and seems to be a suitable proxy
- The group did not consider water and carbon as a qualification of land use, but rather argued for a parallel (not merged) consideration of these issues (e.g. through water and carbon footprints)
- The category "management practices" received a low priority given data constraints

Land use change/conversion

Recommendations and conclusions from the group land use change/conversion are:

- Remove land restoration because this is not an environmental impact.
- Remove land take/sealing because it is a part of the land footprint (besides, cropland, grassland, forest there is also built-up/sealed land)
- The three land use change indicators are interrelated. Land use changes were ranked according to importance for sustainable land use:
  Forest loss (impact on biodiversity, water, GHG emissions)
  Wetland loss (may be equally ranked with forest loss, depending on location)
  Grassland to cropland conversion

There have been extensive discussions on the methodology of calculating a deforestation impact including the time dimension, attribution questions and indirect effects.

Final general discussion

Knut Ehlers: Avoid reinventing the wheel; many issues are covered by other footprints; try not to integrate everything into the land footprint.

Helmut Mayer: When talking about impacts don't forget food processing and transportation of food products.

12 Annex 4: Method for attribution of deforestation to main sectors and primary commodities

The deforestation footprint quantifies the impact of consumption in individual countries and country-groups (including Germany and the European Union) on deforestation. This requires (i) firstly, an estimation of the total land content and deforestation content in primary sectors and commodities; and (ii) Secondly, to track commodity flows from primary production to final use via trade and intermediate products.

This annex describes the methodology applied to achieve the first step, the attribution of gross forest area loss to primary sectors and commodities.

For data availability and practical reasons, this study aims for country-specific averages of transition pathways. Global land use and agricultural data published by the UN form the basis for the allocation of deforestation to primary production of crops, livestock products, timber and natural causes. The Global Forest Resource Assessment (FRA) 2010 provides country-level data of net deforestation for three periods 1990 to 2000, 2000 to 2005 and 2005 to 2010. It provides regional estimates of afforestation rates (and sometimes natural expansion) and of forest land seriously affected by fire.

Land use and agricultural statistics are available from FAOSTAT until 2012/2013. Based on these published global data, calculations by country for the attribution of deforestation to primary production sectors was done separately for two time periods: 1990-2000, 2000-2010.

Attribution of deforestation to sectors and individual commodities follows a three-stage approach:

In a first step, we use the structure of a land-use transition model to attribute deforestation to the following land-use change categories, based on the FAO land use statistics from one year to another:

1. forest land converted to agriculture, i.e. for cropping and livestock production;
2. forest land converted to built-up land, i.e. expansion of urban areas, residential land and transport infrastructure;
3. forest land converted to 'other land[41]' in the process of extraction of industrial roundwood, fuelwood, side effects of agricultural expansion and other 'unexplained' reasons; and
4. forest land destroyed and as such converted to 'other land' due to natural causes (e.g., fire, diseases, extreme events).

Secondly, the deforestation attributed to agriculture is separated into land used for cropping and land converted to pastures for ruminant livestock production. A fraction of agricultural land is allocated to the forestry sector (logging) to account for wood extraction on forest land that has been converted for agriculture.

In a third step, deforestation associated with expansion of crop production is then attributed to specific individual crops.

The per country land-use transition model is based on a non-spatially explicit land-use transition matrix and defined as follows:

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[41] The land use category 'other land' comprises of all land use not classified as agricultural land (i.e. cultivated land, permanent pastures and meadows), forest land (according to FRA2010 defined as minimum 10% canopy cover) and built-up areas. This includes sparsely vegetated shrub land and herbaceous vegetation with less than 10% canopy cover.

Let L_i^t be the extent of land-use category i at time t, with L1 = F (forest land), L2 = A (agricultural land), L3 = B (built-up land), L4 = O (other land), and total land in a country T = F+A+B+O. Then the land use transition matrix describing conversions between time points *t* and *t+1* can be written as:

	Forest	Agriculture	Built-up	Other land	
Forest	m_{11}	m_{12}	m_{13}	m_{14}	F^t
Agriculture	m_{21}	m_{22}	m_{23}	m_{24}	A^t
Built-up	m_{31}	m_{32}	m_{33}	m_{34}	B^t
Other land	m_{41}	m_{42}	m_{43}	m_{44}	O^t
	F^{t+1}	A^{t+1}	B^{t+1}	O^{t+1}	$T^t=T^{t+1}$

Where m_{11} is the fraction of forest land remaining forest land between time point *t* and *t+1*, m_{12}, m_{13} and m_{14} are the conversions of forest land to agricultural land, built-up land and other land between *t* and *t+1*, respectively, and so on. The sum of a row equals the land-use area of the respective land-use category at time *t*, and the sum of a column at time *t+1*.

The available statistical information (FAOSTAT, land use domain[42]) provides annual estimates of L_i^t by country for forest land, agricultural land and total land. The fraction of 'other land' is manually set by the FAO as $O = T - (A+F)$. When considering FAO definitions for deforestation, net deforestation would be $F^{t+1} - F^t$.

In order to obtain a numerical solution for the elements m_{ij} of the transition matrix for each country, a number of additional constraints and simplifying assumptions must be introduced which alter the reported statistics. For the attribution of deforestation to major sectors the following assumptions were adopted:

1. Accounting identities for each sector and for total land

This assumption solves some encountered inconsistencies found in the balances. Land accounts must balance:

$$L_i^{t=1} - L_i^t = \sum_{j\neq i} m_{ji} - \sum_{j\neq i} m_{ji} \qquad (1)$$

where $L_i^t \geq 0$ and $m_{ij} \geq 0$, and $i,j = 1,\ldots,4$.

Here the term on the left side of equation (1) represents net changes of land-use categories as recorded in the available FAOSTAT statistics. In other words the change of a land-use category between two time points (e.g. forest area change) must equal the sum of all changes from other land-use categories (increases, or in the forest example afforestation[43]) minus the sum of all changes into other land use categories (decreases or in the forest example deforestation).

Furthermore, the four broad land-use categories must add up to total land at all time points:

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[42] Available from URL: faostat.fao.org/site/377/default.aspx

[43] Afforestation is the act of establishing forests through planting and/or deliberate seeding on land that is not classified as forest, while reforestation refers to the re-establishment of forest through planting and/or deliberate seeding on land classified as forest, for instance after a fire, storm or following clear felling (FAO, 2010)

$$T^t = \sum_{i=1}^{4} L_i^t \qquad (2)$$

2. Specific conditions for certain elements of the transition matrix

a) Conversion of built-up land

None of the built-up land can be converted into another land-use category in a later period.

Conversion to built-up land is assumed irreversible. All off-diagonal elements in the matrix row referring to built-up land are set to zero:

$$m_{31} = m_{32} = m_{34} = 0 \qquad (3)$$

b) Conversion into forest land or afforestation

All afforestation is modelled via the land category 'other land'. That means land, especially agricultural land, is assumed to be first converted into this category (through degradation or abandonment) and 'other land' is converted into forest land at rates listed in the national reports of FRA 2010 (i.e., Table T5 in those country reports[44]). Where national data are not reported in FRA 2010, afforestation is estimated using average regional afforestation rates derived from the published estimates in the FRA 2010 main report (Table 5.7 on p.96). In the model, this is represented as

$$m_{21} = m_{31} = 0 \qquad (4)$$

and afforestation is set according to national data or estimated using regional coefficients (α_{REG}):

$$AF = m_{41} = \alpha_{REG} \cdot \frac{F^{t+1} + F^t}{2} \qquad (5)$$

c) Conversion to built-up land

The elements m_{i3}, are assumed to occur from all other land-use categories in proportion to their respective extents:

$$m_{i3} = (B^{t+1} - B^t) . \frac{L_i}{(L_1 + L_2 + L_4)} \qquad (6)$$

for $i = 1, 2,$ and 4.

The extent of urban expansion, term $(B^{t+1} - B^t)$, is derived from a spatially explicit land-use database (IIASA/FAO 2012, GAEZ Model Documentation, p.25), which describes the extent of built-up land based on available population distribution data. The spatial population density inventory (30 arc-seconds) for the year 2000 was developed by FAO-SDRN, based on spatial

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[44] FRA 2010 country reports available from URL: http://www.fao.org/forestry/fra/fra2010/en/, for countries which report on natural expansion of forests into other land, these have been included in the afforestation figures

data of LANDSCAN 2003, LandScanTM Global Population Database[45], with calibration to UN 2000 population figures. Landscan is a spatial land-demand function, which estimates the extents of required built-up land area for urban and infrastructure purposes based on population density and distribution (based mainly on data from Asia). It is applied together with changes in population numbers to model increases in built-up land area.

d) Conversions due to fire result in 'other land'

Data presented in FRA 2010 on extents of forest land severely affected by fire were used to provide rough estimates of forest land losses due to natural conditions. In the calculations it is assumed that ten% of the affected forest land is severely damaged and entering the stock of 'other land':

$$dFO = \beta_{REG} \cdot \frac{F^{t+1} + F^{t}}{2} \tag{7}$$

The parameters β_{REG} were calculated from the regional aggregate estimates presented in the main report of FRA 2010 (Table 4.7 on p.75). Where specific additional information was available, e.g. the severe forest fires in Indonesia during 1990 – 2000 and the fires and drought conditions in Australia during 2000 – 2008, the national estimates were adjusted accordingly. As noted by FAO, available data on forest land affected by fire and its causes is incomplete and estimates derived are uncertain (FAO, 2010).

e) Specific conversion assumptions for agricultural land

In addition to conversion for built-up land and losses due to natural conditions (fires, etc.), agriculture is a primary source of deforestation (Boucher, 2011; Houghton, 2010):

$$m_{12} = \begin{cases} dA & if\ dA \leq dFN \\ dFN & if\ dA > dFN \end{cases} \tag{8}$$

And

$$dFN = -(F^{t+1} - F^{t}) + AF - m_{13} - dFO \tag{9}$$

where m_{12} is the conversion of forest land to agricultural land,

dA is total estimated demand for additional agricultural land,

AF is afforestation (equation 5),

$m13$ is conversion of agricultural land to built-up land.

The last term dFO in equation (9) represents natural losses of forest as defined above in equation (7). Afforestation AF and natural losses of forest dFO are parameterized using regional coefficients calculated from results published in FRA 2010 (FAO, 2010) and described above under b) and d).

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[45] Available from URL: http://www.ornl.gov/landscan/

dFN is the remaining gross forest area change (net forest change plus afforestation) minus forest land converted to built-up minus forest land lost due to natural conditions (fires).

Changes in reported expansion of cultivated land and pastures alone may conceal important deforestation effects of agricultural expansion. Therefore additional available information from FAOSTAT on changes in harvested areas, ruminant livestock numbers, and expansion of selected perennials may increase cultivated land expansion when they are larger than cultivated or pasture land expansion. When a country reports significant increases in harvested cultivated areas while reported cultivated land expands little, the methodology checks for the plausibility of the implied land-use intensification and uses the harvested area expansion to estimate additional physical land demand. Historic analysis of global crop production evolution suggests that on average about a third of the sources of crop production increases were due to harvested land expansion and two thirds due to yield increases with strong regional variation between developed and developing countries (Bruinsma, 2003, p.126).

dA or additional agricultural land demand is estimated as gross demand which is comprised of net increases of cultivated land *dC* and pastures *dP* which include losses due to degraded and abandoned agricultural land. *dC* and *dP* calculate maximum increases of cultivated land and pastures, respectively, based on reported expansions and other parameters from FAOSTAT, according to:

$$dA = dC + dP \tag{10}$$

and

$$dC = max(C^{t+1} - C^{t}, \gamma_{REG} . \Delta H^{P}, \delta_{REG} . \Delta H^{A}) + D^{C} + E^{C} \tag{11}$$

$$dP = max(P^{t+1} - P^{t}, \vartheta_{REG} . \Delta RLS) + D^{P} + E^{P} \tag{12}$$

where variables C and P represent respectively reported cultivated land and permanent pastures and meadows.

ΔH^{P} are changes of reported harvested areas of selected perennial crops (banana and plantain, coffee, cocoa, tea, oil palm fruit, and natural rubber). These selected perennial are likely to be established on newly converted former forest land rather than replacing former cultivated crops because of their biophysical and agronomic management practices.

ΔH^{A} are changes of harvested area of all other crops during the observation period.

Variable ΔRLS measures the changes in ruminant livestock numbers (mainly cattle, sheep and goats) converted to reference units.

These variables are adapted by regional parameters γ_{REG}, δ_{REG}, and ϑ_{REG} respectively.

A fraction of the total agricultural land stock is assumed to be lost due to land degradation and abandonment every year. In addition agricultural land conversion may result in edge effects, e.g. by clearing by fire may destroy forest without entering the stock of cultivated land. The terms D^{C} and D^{P} represent land lost due to degradation, E^{C} and E^{P} were included to account for 'edge' effects', i.e. a fraction of land wasted (and converted to 'other land') in the process of land conversion to agriculture. When land is prepared for agricultural use, in most cases the 'preparation' has an effect on the surrounding land, while these surroundings will not end up in national agricultural land-use statistics as they are not productive. This kind of deforestation is attributed to the agricultural sector but in the transition matrix this forest land is converted into ‘other land’. So, deforestation because of these effects is attributed to the agricultural sector but does not result into more agricultural land. Note that only very limited country-specific information is available to parameterize these effects and therefore regional coefficients and assumptions were used in the model.

f) Remainder allocated to ‘other land’

All forest area loss that cannot be attributed to the expansion of crops, livestock and built-up land, or natural causes (mainly wildfires), even with the assumptions above, is conversion into ‘other land’. Activities and drivers causing such deforestation differ between regions. This remainder can be attributed as ‘unexplained’.

With the conditions and assumptions described in 1) and 2) above, the land use transition matrix M, which describes changes for the period (*t, t+1*), respectively for 1990-2000 and 2000-2008 in this study, is fully determined. The resulting flows and estimation method are summarized in the matrix below (Table 19) and sketched in Figure 12.

Table 19: Land use transition matrix

	Forest	Agriculture	Built-up	Other	
Forest	m_{11}	m_{12}	m_{13}	m_{14}	F^t
Agriculture	m_{21}	m_{22}	m_{23}	m_{24}	A^t
Built-up	m_{31}	m_{32}	m_{33}	m_{34}	B^t
Other	m_{41}	m_{42}	m_{43}	m_{44}	O^t
	F^{t+1}	A^{t+1}	B^{t+1}	O^{t+1}	$T^t=T^{t+1}$

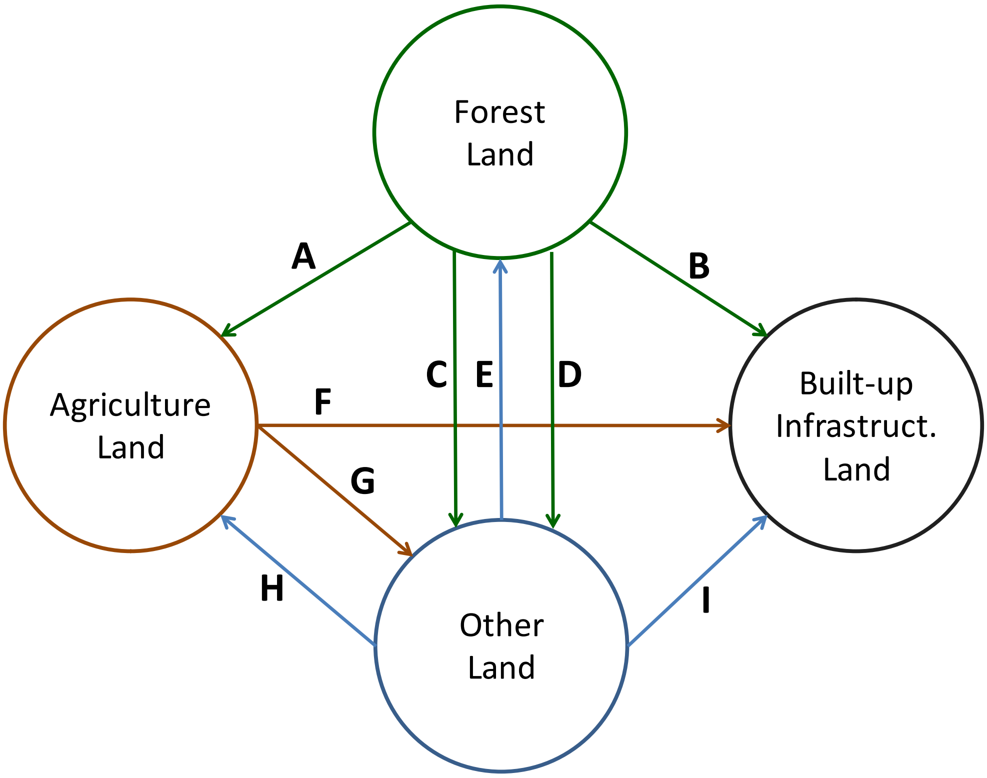
Matrix elements derived using the basic land-use accounting identities, described in 1) above, are shown in blue. Elements resulting from condition 2 a) are shown as grey. Conversion to forest, i.e. afforestation, is defined under 2 b) and shown in yellow. Conversion to built-up land is specified in 2 c) and shown in a red tone, and remaining conversions between agriculture and ‘other land’ result from conditions 2d), 2 e) and 2f) and are shown in green.

The main objective, estimation of deforestation by broad sectors, is given by the off-diagonal elements of row 1, i.e. elements m_{12}, m_{13}, and m_{14}.

The various land conversions (flows) shown in Figure 12 and included in the model calculations refer to the following elements:

A = Clearing of forest land for agricultural use; B = Clearing of forest land in the expansion of built-up and infrastructure land; C = Deforestation unexplained or caused by unsustainable logging; D = Forest land lost due to natural causes (mainly wildfires); E = Afforestation (including natural expansion of forest land); F = Conversion of agricultural land for the expansion of built-up and infrastructure land; G = Loss or abandonment of agricultural land; H = Conversion of other land for agricultural use; I = Conversion of other land for the expansion of built-up and infrastructure land.

Figure 12: Land conversion flows included in the attribution of deforestation to broad sectors



1. Proportionality assumption

In order to attribute deforestation to the two subcategories of the agricultural sector, element m_{12}, i.e. cropping and ruminant livestock production, an additional quite natural assumption has been made, namely that deforestation can be attributed in proportion to total additional land demand of each agricultural sub-sector. In other words, we impose the conditions:

$$dF^C : dF^P = dC : dP \qquad (13)$$

And

$$dF^C + dF^P = m_{12} \qquad (14)$$

In this formulation, the terms dF^C and dF^P respectively represent deforestation attributed to the primary agricultural sub-sectors of cropping and ruminant livestock production, and dC and dP the expansion of cultivated land for crop production and pasture land for ruminant livestock production as defined in equations (11) and (12). Each agricultural sub-sector contributes directly and indirectly to deforestation. For example cropland expansion may be attributed to deforestation indirectly by occurring on land outside the deforested areas while pasture expansion is the direct agent of deforestation.

2. Wood extraction on forest land converted for agriculture

Conversion of forests to agriculture is in some regions preceded by timber extraction. Sometimes natural fires may pave the way for agricultural expansion. We assume a certain fraction of deforestation attributed to agricultural expansion to reallocate to the roundwood extraction. This fraction varies and is set by region, at 0-10% based on expert knowledge.

3. Allocation of deforestation to individual crops

After allocation of deforestation to broad sectors, including to agriculture for the expansion of crop and livestock production, the extents assigned to crop agriculture are attributed to individual crops in the following way. First, crops are divided into two groups:

(i) Group I_1 includes perennials, which are frequently being established on forest land rather than replacing former cultivated crops because of their biophysical, agronomic, phyto-pathologic requirements and field/plantation management practices. These perennials include oil palm, rubber, banana & plantain, coffee, cocoa and tea.

(ii) Group I_2 includes all other crops.

Secondly, based on the national details of the calculation to determine total demand for additional crop land dC (see condition 2e) in the description above), the extent of deforestation attributed to crop agriculture dF^C is split into amounts allocated to the two crop groups, namely $dF_{I_1}^C$ and $dF_{I_2}^C$.

Thirdly, within each crop group, extents of deforestation are then attributed in proportion to each crop's magnitude of harvested area expansion.

$$df_i = \frac{dF_{I_1}^C \cdot dH_i^+}{\sum_{j \in I_1} dH_i^+} \quad \text{with } i \in I_1 \tag{15}$$

and

$$df_i = \frac{dF_{I_2}^C \cdot dH_i^+}{\sum_{j \in I_2} dH_i^+} \quad \text{with } i \in I_{12} \tag{16}$$

where crop-wise harvested area expansion dH_i^+ is calculated as

$$dH_i^+ = \max\left(0, H_i^{t+1} - H_i^t\right) \text{ for both } i \text{ and } j\text{, with } \quad i \in I_1 \text{ and } j \in I_2 \tag{17}$$

H_i^t is the harvested area of crop i at time point t.

The underlying principle followed here is that deforestation can be caused both by direct conversion as well as indirect factors (e.g. displacement of crops or pastures, distant effects of crop expansion) and that attribution of deforestation is best based on the relative magnitude of land demand reported for each crop sector in terms of expansion of respective harvested areas. Thus all crops in a country reporting expansion of harvested areas are attributed to deforestation in relation to their relative contribution to agricultural expansion.