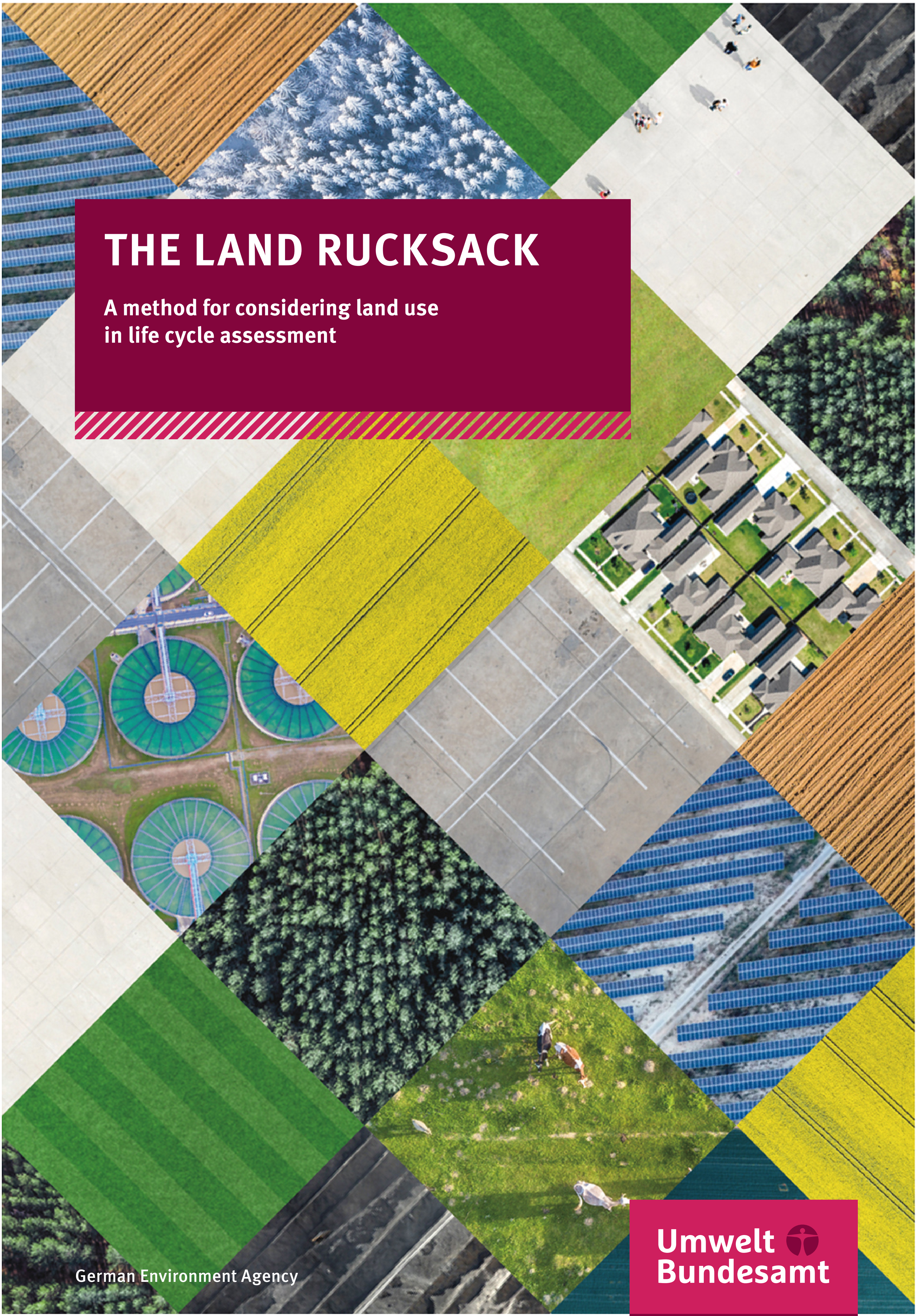

THE LAND RUCKSACK

A method for considering land use in life cycle assessment

German Environment Agency

Umwelt Bundesamt

Imprint

Publisher:
German Environment Agency
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Design:
www.suwadesign.de

Publications as a pdf:
www.umweltbundesamt.de/publikationen

Photo credits:
iStock.com/Evgeniy Alyoshin, Naeblys, Biletskiy Evgeniy, hudiemm, Orbon Alija, cicloco, Kyryl Gorlov, Naypong, Art Wager, nonnie192, antos777, AvigatorPhotographer, Jevtic

As at: April 2022

ISSN 2363-832X

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Abbreviations

Abbreviation	Definition
aa-eq	artificial area equivalent
aLUC	attributional land-use change
APC	average per capita
B7	Diesel fuel blend with up to 7% biodiesel by volume
BWI-3	Third German Forest Inventory (Dritte Bundeswaldinventur)
CSP	concentrating solar power
Destatis	German Federal Statistical Office (Statistisches Bundesamt)
dLUC	direct land-use change
DNP	distance-to-nature potential
RE	renewable energies
FAO	Food and Agriculture Organization of the United Nations
FU	functional unit
FSC	Forest Stewardship Council
FT	Fischer-Tropsch
HNV	high nature value
iLUC	indirect land-use change
ISO	International Standard Organisation
JRC	Joint Research Centre
LCA	life cycle assessment
LUC	land-use change
MENA	Middle East North Africa
NIR	National Inventory Report
Pkm	passenger kilometre
PNV	potential natural vegetation
PtL	Power-to-liquid
PV	photovoltaic
RED	Renewable Energies Directive
SETAC	Society of Environmental Toxicology and Chemistry
UBA	German Environment Agency (Umweltbundesamt)
UNEP	United Nations Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
WZI	alternative forest condition index (alternativer Waldzustandsbericht)

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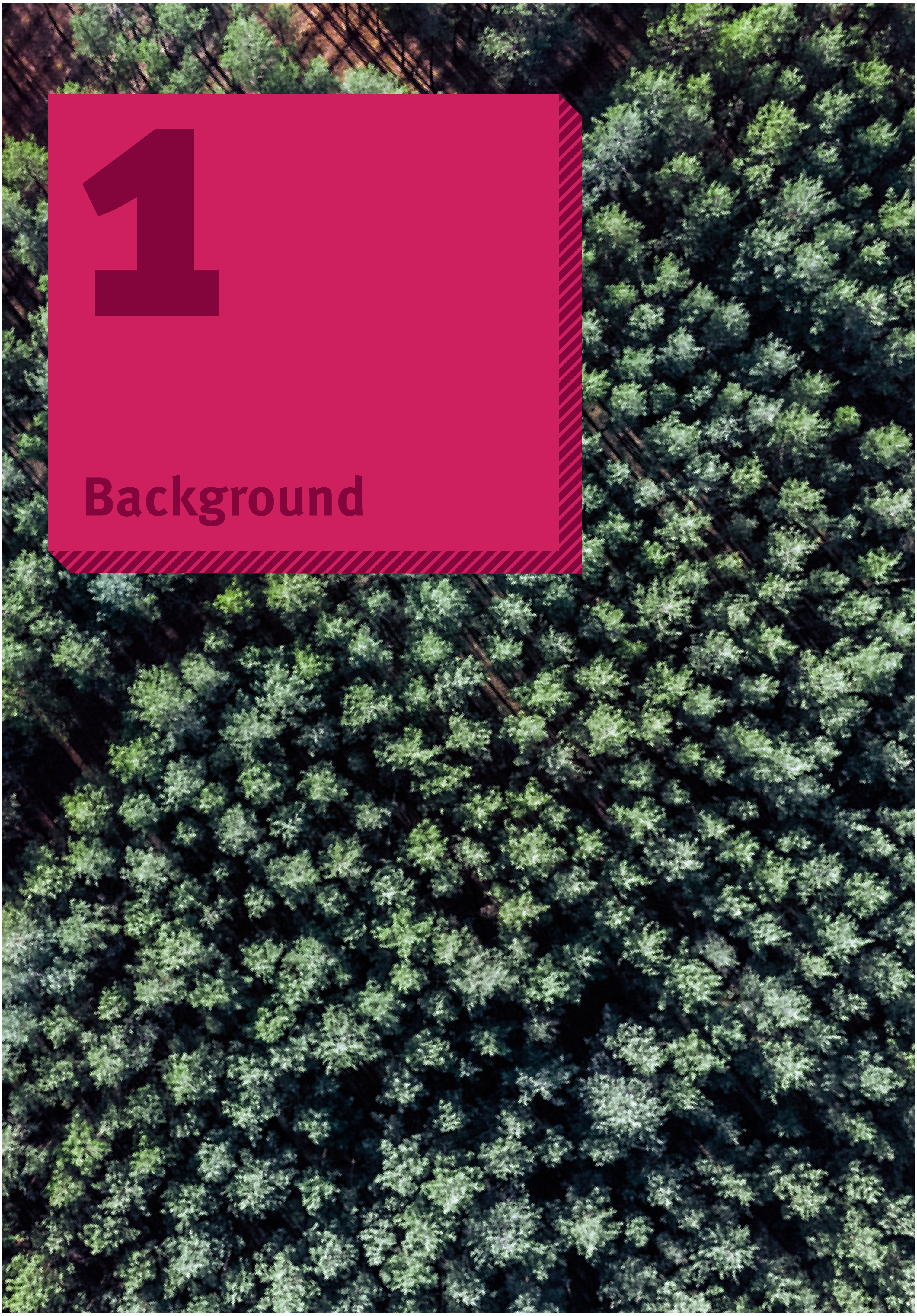
Background



1 Background

Life cycle assessments (LCA) are an essential tool to explore the environmental impacts associated with a product or service over the course of the entire life cycle. For accurate modelling, data on all relevant potential environmental impacts should be included in an LCA.

A number of standards provide compilations of relevant impact categories (JRC 2011; European Commission 2013; Frischknecht et al. 2016; Frischknecht and Jolliet 2019). Almost all standard works include the impact category land use. Unlike climate change, however, there is no universally accepted approach for assessing the environmental impacts of land use. So which environmental effects caused by land use should in fact be considered in LCA studies? How does one square metre of sealed land compare to one square metre of a wheat field or forest? To consider land in the context of an LCA, the quality of the land used to supply a product or service is a key factor.

There are a number of different approaches to include the impact category land use in LCA. The aim is to record the environmental impacts associated with the type of land use, to assess their extent and to evaluate them like other impact categories. The German Federal Environment Agency (Umweltbundesamt, UBA) (Schmitz and Paulini 1999) has already introduced an approach to model the impact category “natural land use” and proposes hemeroby as a measure for land quality. This so-called UBA assessment method considers the intensity of human intervention on the land area under investigation. Other approaches focus on the loss of biodiversity (Chaudhary and Brooks 2018) or the quality of soils (Bos et al. 2016; Milà i Canals et al. 2007).

The use of the hemeroby concept proposed in the UBA assessment method has been further developed in recent years (Fehrenbach et al. 2015; Lindner et al. 2020). However, widespread application is still limited due to lack of comprehensive data sets. In addition, the approach has not yet been adapted for all types of land use. An extension and differentiation of the approach is necessary, particularly for the modelling of raw material extraction and settlements. In consequence, the research project Land rucksacks of goods and services (Fehrenbach et al. 2021a, 2021b, 2021c) was carried out to close such gaps and provide a method for application in LCA. The aspects of land occupation and land transformation were both considered.

Why not rely on other existing methods? A number of sound and well-developed approaches already exist and are briefly reviewed in Chapter 2. However, the hemeroby concept is associated with two distinct advantages. It has now been advanced to differentiate data on products and services according to individually definable requirements. This allows a high degree of specificity and resolution for products, which is in fact necessary for integration with national databases. Moreover, which efforts should be made for conservation in light of different environmental impacts? The definition of the safeguard subject varies widely across different methods. With the decision for of hemeroby as a measure of the total negative environmental impact, other methodological developments are ruled out.

The brochure introduces an approach to include land use in LCA in a comprehensive and user-friendly manner. Thus, key questions can be answered, e.g. which land rucksack is associated with individual goods and services in Germany? The research project Land rucksacks of goods and services provides an answer with a novel method for integration of the different aspects of land use in LCA.

In the following, a summary of the wide-ranging results of the project is presented in compact form. It is aimed first and foremost at LCA experts, but also at stakeholders and policy-makers charged with implementing strategies and measures for the protection, conservation and sustainable use of land, biodiversity and ecosystems.

The complete results may be found in three individual UBA reports. Final Report Part I (Fehrenbach et al. 2021a) describes the underlying methodology. Final Report Part II (Fehrenbach et al. 2021b) presents the results of an application test of the method in four case studies, and Final Report Part III (Fehrenbach et al. 2021c) provides detailed documentation and explanations of baseline data and references to suitable data sources.

2

Land use

2 Land use in life cycle assessment

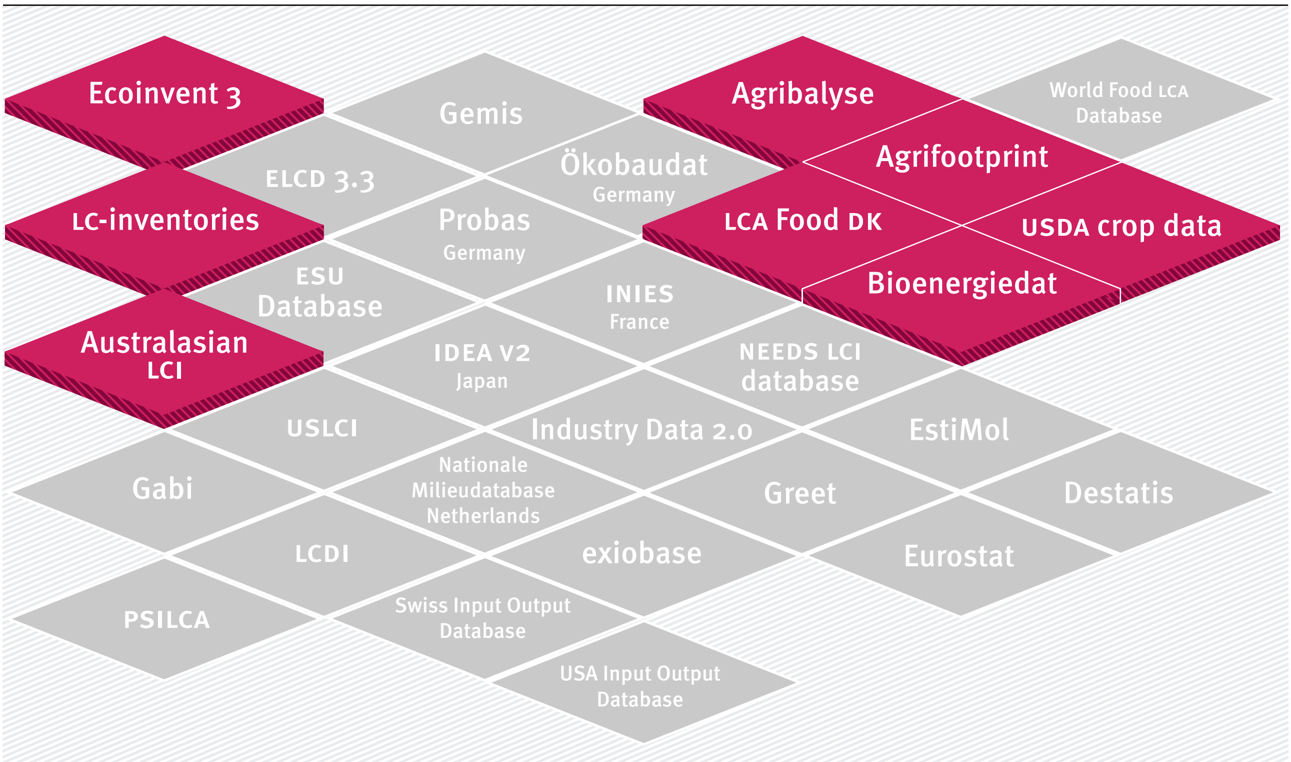
2.1 Review of the status quo

LCA is an instrument to analyse complex systems associated with the life cycles of products and services. Environmental impacts are assessed as impact potentials. Local conditions can only be taken into account to a very limited extent. This should be highlighted because land use is strongly site-specific. However, LCA is not used to assess the environmental impact of, for example, individual construction projects or landscape management plans. Product life cycles in general provide limited spatial resolution. For instance, in an LCA for a loaf of bread or a wooden table, the field on which the grain was grown and the forest from which the wood was harvested remain abstract. But even in the abstract, areas of land differ in quality. The hemeroby – i.e. the intensity of human intervention in an area – may be different when growing wheat compared to growing maize. It differs between organic and conventional farming. A near-natural mixed beech forest differs from a spruce plantation in the same way as a small-scale gravel extraction site differs from an open-cast lignite mine that extends over many square kilometres.

The level of resolution at which an LCA operates thus makes precise but broad distinctions. A consistent methodology is needed to define the categories for land quality. In addition, robust data are needed to quantify the differences between the various land uses. A range of data sources and databases are available for use in LCA. However, very few provide data on land use and land-use change, as illustrated in Figure 1. The calculation of land occupation per product produced is only the first step. The second step requires additional information on land quality, which depends on the type of use. Of the databases investigated, only the widely used LCA database ecoinvent provided an approach here by separating land occupation into use classes according to the so-called CORINE classification. Since other LCA data bases use ecoinvent, this approach is common.

Figure 1

Analysis of data on land occupation and land transformation available from existing LCA databases



Life cycle inventory data on land occupation and transformation are available at process level (ecoinvent – nomenclature)

Reference: Fehrenbach et al. 2021

After assessment of the status quo, ecoinvent was therefore identified as the only existing baseline that includes comprehensive data on land use in combination with a use-related quality indication. Incidentally, ecoinvent also provides data on land-use change.

Would it not be efficient to simply adopt the data and land-use classes from ecoinvent for the concept of the land rucksack? Unfortunately, this would fail to realise the ambition underlying the concept.

The land rucksack seeks to achieve

- high resolution of products and types of land use, as well as
- integration with national databases.

Furthermore, in light of the above goals, the assessment of land use should be based on hemeroby. Once again, ecoinvent and other database systems are not sufficient for this purposes.

Infobox 1: How to do an LCA?

LCA explores harmful environmental impacts caused by products or services over their entire life cycle. It thus links various harmful effects via a chain or a network of many processes in one system. Principles and rules for carrying out life cycle assessments are internationally standardised in accordance with ISO standards 14040:2006 and 14044:2006. The steps of a life cycle assessment include

- definition of goal and scope,
- life cycle inventory analysis,
- life cycle impact assessment,
- interpretation of results.

Since the standards allow considerable flexibility in the specific design of an LCA, the definition of the **goal** and clear indication of the **scope** of any study is a key step. Without it, the LCA is hardly meaningful and interpretable. This step also defines exactly which product or service is subject to the assessment. This is referred to as the **functional unit** (FU), e.g. one kilowatt hour of electricity, the supporting structure for a building or a 100 km car journey.

In the **life cycle inventory**, the inputs (consumption) and outputs (products, emissions, waste) are quantified across all processes of a system. This usually involves an elaborate set of data tables, for which special software models and databases are required.

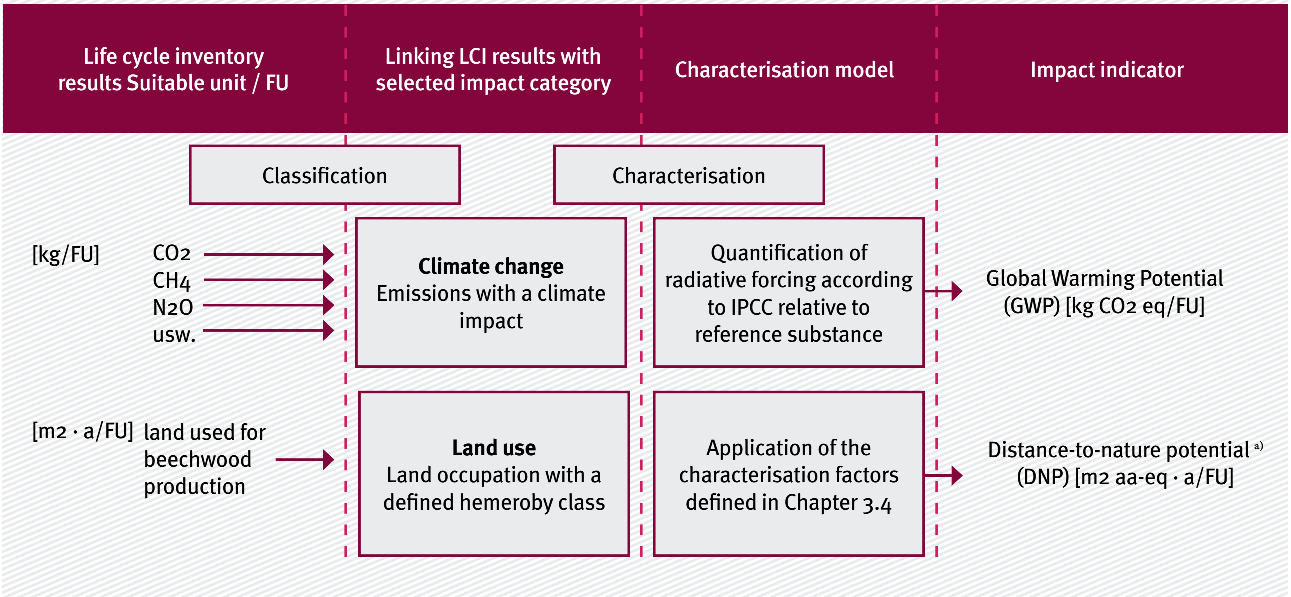
The **impact assessment** assigns the results of the life cycle inventory to different impact categories according to scientifically based criteria in a first step. This step is called **classification**. An impact category summarises the environmental impact of the individual substances on an environmental topic such as climate change, acidification or summer smog. The extent to which the individual emissions contribute to the respective impact category is determined by means of impact factors. Example: Methane contributes 29 times more to global warming than CO_2. This step is called **characterisation**. With the mapping of life cycle systems, the results of the LCA are spatially and temporally indeterminate. Whether a molecule of an acidic pollutant has an acidifying effect depends on where it precipitates. However, the LCA does not provide this information, which is why the exact effects cannot be determined. Instead, potential effects are calculated.

The **interpretation** of the results obtained in the previous steps is the final step. Parameters that are essential for the results are identified and the consistency and integrity of the study are verified. Sensitivity analyses may be carried out to gain insight into the uncertainties associated with the results. Finally, recommendations are made according to the goals defined at the outset.

Figure 2

Impact assessment – characterisation model addresses selected quality

Linking quantity (inventory data) with quality (environmental impact)



[a] Distance-to-nature potential definition in Chapter 3.4

Reference: Fehrenbach et al. 2021

2.2 What are the approaches to date?

To consider land use in the context of LCA, the following information is essential: the size of the land in use, its quality, the duration of use and its condition prior to use. Two variables are considered. First, the size of the area occupied for a certain period of time in order to produce a product (land occupation). In addition, land transformation plays a central role (Frischknecht / Jolliet 2019). This refers to the size of the area that is converted from one form of use to another to manufacture a product. This conversion can be caused by direct and indirect effects (Köllner et al. 2013). Each form of land use has specific consequences for the environment. To fully understand the environmental impacts of the system under study, it is therefore necessary to determine how land is used along the entire value chain. To capture the change in quality of the land, various indicators were proposed in the development of LCA.

The basic framework as well as the requirements and guidance for life cycle assessments are laid down in two standards of the International Organisation for Standardization (ISO), **DIN EN ISO 14040** and **DIN EN ISO 14044**. Although land use is mentioned there, no further details are given on how it should be applied in practice. As a result, a number of approaches to assessing land use based on indicators have emerged in practice, which are published in various manuals and guidelines for performing LCA. The **CML method** of the Centrum voor Milieukunde (CML) of Leiden University was already developed in 1997-2001. It addresses a spectrum of consequences of human land use with the so-called impacts of land use, separated into competition for land, loss of biodiversity and loss of life-support function. The latter is synonymous with the nowadays commonly used term ecosystem services. The CML method highlights that the integration of land use into LCA is very complex and poses a great challenge because LCA essentially considers material flows (inputs such as raw materials and outputs such as emissions). However, land does not behave like a material flow. In addition, there are qualitative aspects such as the loss of ecosystem services and biodiversity as impacts of land use. In the CML method, therefore, no characterisation methods were initially proposed.

The **UNEP-SETAC Life Cycle Assessment Initiative** guidance documents address land use considering impacts on biodiversity (2016) and soil quality (2019). The proposed models are based on the two fundamental variables of land occupation and land transformation. The biodiversity loss model is based on the indicator species richness. It takes into account the local effect of different types of land use on biodiversity, links land use to species loss, considers the relative rarity of the ecosystems affected and includes the threat level of the species (Frischknecht et al. 2016). For soil quality, UNEP-SETAC proposes to consider soil carbon deficit potential and erosion potential in addition to land cover and land conversion (Frischknecht and Jolliet 2019).

Another approach may be found in the Dutch **ReCiPe method** (2016). Again, the processes of land occupation, land transformation and land recovery are considered. Likewise, the relevant indicator is species richness on the land used for production.

The Japanese **LIME model** (2018) provides another method for assessing the damage to biodiversity and primary production caused by land use. The LIME method assesses the risk of vascular plant extinction in Japan caused by land conversion based on analyses for 2000 species. The representative value for damage factors in Japan was calculated by conducting an analysis for each type of land use. Damage factors extended to 193 countries around the world were then developed using data from the International Union for Conservation of Nature and Natural Resources (IUCN).

The focus on biodiversity mapped as species richness on a given area was used by Chaudhary and Brooks (2018) in a model to determine so-called **potential species loss**. This can be used to determine potential species losses in each of the 804 terrestrial ecoregions worldwide in five broad land use types (managed forests, plantations, pasture, cropland, urban) assuming three intensity levels (minimum, light and intensive use).

In contrast, a method that focuses on soil quality is recommended, for example, in the **International Reference Life Cycle Data System** (ILCD), which quantifies the loss of soil organic matter (JRC 2011).

A new tool that closely follows the LCA methodology is the 2018 EU **Product Environmental Footprint** (PEF) (European Commission 2013). The PEF addresses the following aspects of land use: soil quality, biotic production, erosion resistance, mechanical filtration and groundwater replenishment. Soil quality is adressed with the so-called soil quality index.

The various approaches used in life cycle assessments all seek to represent highly complex, multifactorial interactions in a simplified way using as few representative indicators as possible. It does not matter whether the focus is more on biodiversity or on soil quality - the data needed as a baseline are mostly unavailable. It therefore seems appropriate to change the perspective and focus on the intensity of human intervention during the production process instead. This intensity of intervention with the land can be characterised as hemeroby.

2.3 Why choose hemeroby as an indicator?

Hemeroby as a means to assess land use in LCA was first suggested by Klöpffer and Renner (1995). The proposed method was based on the habitat and vegetation type classification system developed by Sukopp (1972). The approach for forests by Giegrich and Sturm (1996) was based on these initial works. It was later integrated into the so-called UBA assessment method by Schmitz and Paulini (1999), resulting in the impact category of natural land use. Since then, the concept has been continuously advanced (Fehrenbach et al. 2015). The original classification with the categorisation into naturalness classes and the use of the term "closeness to nature" was replaced by the term "hemeroby" in the further development of the concept. The reason for this was that the concept of naturalness assumes the original natural vegetation [1] as a reference, at least among German experts. Naturalness thus takes a historical perspective and represents a measure of similarity to the original situation that is untouched by human intervention (Stein 2011). In contrast, hemeroby places the focus on the current status and asks: How strong is human intervention on the land used for a specific purpose? The reference here is the state of a habitat or ecosystem that would arise from self-regulation based on the current site-specific potential.

In fact, the potential natural vegetation is unsuitable as a reference for all types of land use and ecosystems apart from forests. This is true at least in regions where forest always represents the climax community of the natural vegetation. Under no circumstances can an agricultural field have anything in common with the forest that would develop if the area was left to follow natural succession. Whether the field is

1 Specifically, the current potential natural vegetation

cultivated with higher or lower intensity makes no difference to the "distance" by which it is removed from the potential undisturbed forest. This equally applies to species-rich grasslands and settlements. In contrast, the degree of hemeroby allows differentiation based on criteria characterising the intensity of intervention on the land. For forest ecosystems, a limited reference to the potential natural vegetation is obvious and appropriate. The naturalness of the tree species composition is a suitable and typical criterion that addresses both angles. A forest including many non-natural species (as it is mostly the case in German forests) is a clear indication of human intervention, i.e. planting of desired species (spruce, pine, Douglas fir) changes both forest appearance and quality.

Which safeguard subject is addressed with hemeroby?
The key element for the definition of an impact category is the underlying safeguard subject. While this is a given in the case of climate change (protection of the climate), it is by no means clearly defined in the case of land use. Here it is necessary to clarify which of the many possible negative environmental impacts poten tially associated with land occupation should be considered. Examples include sealing, destruction of soil and its functionality, or other ecosystem services, loss of biodiversity, loss of naturalness, to name but a few.

By adopting hemeroby as a measure for assessing the ecological quality of land, avoiding or reducing hemeroby is also the goal. The subject to be safeguarded would thus be an environment with the lowest possible level of human intervention. A more precise definition can be derived from the definition of the degree of hemeroby presented by Kowarik (2004). According to this definition, the **safeguard subject is the self-regulatory capacity of an ecosystem on the basis of the current site-specific potential.** This self-regulatory capacity is reduced with rising intensity of human intervention. The great advantage of considering the intensity of intervention lies in the fact that a whole spectrum of negative environmental impacts can thus be covered. The restriction to a single aspect as a proxy for the multitude of environmental impacts on the area is no longer necessary.

In principle, land used for production purposes cannot be free of human intervention. The objective of the underlying safeguard subject here is not to remove as much land as possible from use and thus from human influence. Rather, the aim is to keep intervention as low as possible.

2.4 Motivation for the land rucksack study

The motivation for the land rucksack study arose from the considerable range of methodological approaches on the one hand, and the question of data availability on the other. Data on land occupation are mostly available, while less is known about land transformation. For both variables, the necessary data were not available in the required resolution by product at the outset of the project. Furthermore, data were often out of date and could not be updated. More crucial, however, was the question of whether the methodology for assessing land use in LCA via human intervention intensity is sufficiently developed and whether its application is possible using the available data.

The land rucksack approach describes the quality of the land as a consequence of the way in which it is used. The decision for hemeroby as a characterisation variable revealed that the current available data are insufficient. In the second step, therefore, these data gaps were filled wherever possible and a comprehensive assessment concept was developed. Finally, the approach was applied in three case studies. The land rucksacks of (1) electricity production in Germany, (2) passenger transport (car) for a journey of 100 km and of (3) various construction materials were modelled. In another example, green hydrogen and electricity-based fuels were analysed. These results are included in the transport case study.

What are the implications for this study?

- Data on land occupation and also land transformation are available, but not in the required resolution by product. Moreover, these data are often out of date and cannot be updated.

- Quality of the land as a consequence of the way it is used (characterisation, see Info box 1): the data available to date are insufficient for hemeroby as a characterisation variable.

3

Methodological concept

3 Methodological concept of the land rucksack

3.1 Key output variables

At the life cycle inventory level, the land rucksack applies both quantitative data in the physical unit square metre and qualitative data, i.e. information on the hemeroby of the area in use. For the quantitative data, a distinction is made between two basic variables:

1. Land occupation during the time of use (temporary land occupation)

2. Land transformation associated with land use.

At the life cycle inventory level, the correlation with land quality must also be established, as the life cycle inventory should already provide the necessary information for the impact assessment. In the case of climate change, this information is inherent in the nature of the chemical compounds (CO_2, methane, nitrous oxide, etc.). For land use, the type of land or its use should therefore be classified as appropriate. Simply stating the square metres in use multiplied by the duration of the use period, i.e. area x time, is not sufficient as an impact assessment. The key variables are explained below.

3.1.1 Land occupation

In contrast to alternative terms such as land use, land take or land consumption, the land rucksack employs the term land occupation. It refers to the area that is occupied for the production of a product or the provision of a service for a defined period of time and thus unavailable for any other use. Due to the link to the time of use, the correct term is temporary land occupation, which is always implied in the following when referring to land occupation.

The unit of temporary land occupation is m² x time unit per functional unit (FU). The unit of time is defined as one year. In practical terms, this corresponds to the area under cultivation for an annual harvest in the case of an agricultural product. For forest wood it is essentially the same, i.e. the forest area for the annual extraction of wood is taken into account. However, the forest area must be defined in detail: with or without forest roads (which are necessary for management), with or without unmanaged forest areas. In the case of a wind turbine, the area occupied also counts towards the amount of electricity generated over a year. It is irrelevant how long the service life of such an installation is. After all, this question does not arise for fields or forests either. The situation is different in extraction areas used for raw material mining. Here, it is not only the area where mining is carried out for a year that counts, but also how long this area will be unavailable for any other use due to mining impacts.

Here, the key principle of temporary land occupation is once again apparent. Double counting or non-counting of land is avoided under all circumstances. The basic principle is: The area per unit of time that is not available for another use in the same unit of time (i.e. for the provision of other products or services) is to be credited as occupation to a product or service. For the example of the wind turbine, this means that, e.g. the mandatory distance between the turbines is irrelevant if these spaces are used for other purposes, e.g. for agriculture. However, if the use is restricted, as for example in the case of wind turbines in forests, where no forestry can take place within a certain radius around the turbine, then this area is to be included in the land occupation of the turbine.

Thus, land occupation in the land rucksack follows the definition of the UNEP/SETAC-Life Cycle Initiative (Frischknecht et al. 2016) that is applied by the LCA community.

3.1.2 Land transformation

In addition to land occupation, the land rucksack considers land transformation as a second component, once again in analogy to the UNEP/SETAC-Life Cycle Initiative (Frischknecht et al. 2016).

Land transformation addresses the change in land quality associated with the supply of a product or service. A number of different methodological concepts to describe and quantify land-use change are already available. These include direct and indirect land-use change. The context of application is essential for these concepts.

Emission reporting according to UN Framework Convention on Climate Change (UNFCCC) [2] requires nations to report annually on greenhouse gas emissions

2 United Nations Framework Convention on Climate Change

caused by land-use change (LUC). The calculation of emissions is based on land-use change balances: conversion of grassland to arable land, forest land to settlement, etc. Therefore, official data are available for each reporting country. However, these LUC data cannot be attributed to individual products.

In contrast, a very direct link to products is established in the methodology of the Renewable Energy Directive (RED)[3] . Here, certified evidence must be provided for each delivery of a specific product as to whether land-use change has taken place at the origin of feedstocks in the years after 2008. This methodological approach is called direct land-use change (dLUC). The regulations of the RED refer exclusively to the product biofuels. The producers of biofuels therefore ensure that the raw materials for their products (e.g. palm oil) do not originate from areas where dLUC takes place. Instead, the raw materials for other products (food or animal feed, material products such as soap or cosmetics) can be supplied from these areas, for which there is no RED regulation. The approach is therefore criticised for not avoiding land-use change per se, but only shifting it between different products.

The concept of indirect land-use change (iLUC) has emerged from the criticism of dLUC. The iLUC approach focuses on the global market for goods. If an incentive is set for increased production, e.g. with the biofuel quota of the RED, this creates a demand for new cropland. It is irrelevant whether the additional product itself comes from this new land under cultivation, as everything is linked via the common market. In the case of palm oil biodiesel, rapeseed oil and all other competing vegetable oils are also represented in this market. This is why the market-based models also calculate iLUC for rapeseed biodiesel due to primary forest clearance, e.g. in Indonesia, even though no rapeseed is actually cultivated on Indonesian land.

There is no uniform and universally accepted modelling approach for calculating iLUC. Nevertheless, these model calculations support decision-making, for example when certain products are c onsidered for promotion through political strategies or instruments. However, they do not provide information about the status quo and thus not about a product per se. To return to the example of palm oil: If forest clearing for new plantations is indirectly attributed to biodiesel, this removes any burden from the products that are actually produced from the palm oil produced there (e.g. chocolate). The iLUC approach is therefore not suitable for generating data for LCA of a specific product.

What does it take to adequately integrate land-use change into LCA? Evidently, an approach that meets all requirements and every wish and demand remains elusive. Conventions and limitations of the system boundary cannot be avoided. To generate data at the life cycle inventory level, a so-called attributional approach is required. In this context, attributional means that all de-facto environmental impacts that can be empirically quantified are attributed to all products that are associated with the respective impact. Since the attribution step is also referred to as allocation, this term is also frequently used for the attributional approach. For the example of palm oil, this implies that the land-use change that actually occurs for the expansion of palm oil plantations is attributed to the total production of palm oil. In consequence, the land-use change caused by palm oil is charged equally to all products made from palm oil (biodiesel or chocolate). In most cases, however, land-use change cannot be specifically attributed to a particular agricultural product such as palm oil, for example in the case of annual crops with crop rotation, a common agricultural practice in Germany. However, the approach could be applicable for cases in which a specific crop is associated with considerable gains in cultivation area.

The national inventory reports (NIR) for the UN Framework Convention on Climate Change can be used for the attributional land-use change (aLUC) approach applied here. Thus, an empirical and official data set is available. For countries that are not subject to reporting requirements, comparable data on land-use change are available from the FAO (FAOSTAT 2021).

What does the aLUC approach entail considering the spatial and temporal dimension? The application of accounting at the national level is associated with a number of consequences, e.g. responsibility for aLUC is assigned to the countries in which the land-use change takes place, not to markets and transnational trade relations. This approach therefore does not resolve the concern of iLUC. Considering the

3 Renewable Energy Directive: Rugelation 2009/28/EU, since updated RED II: Regulation (EU)2018/2001

temporal dimension, it should be noted that the data on LUC always describe the past. The methodological approach here recommends averaging the available data over the last five years to smooth fluctuations in individual years. It is thus assumed that the recent past is also sufficiently meaningful to serve as the basis for LCA input data for current and future application. This underlying assumption must be carefully monitored in the case of processes that are highly dynamic. A case in point here may be found in the case study below on the expansion of wind energy and photovoltaics, market segments that have shown significant growth in recent years. In mathematical terms alone, this leads to relatively high values for land-use change. The effects of land-use change are even more extreme in the case of technologies that are currently not very widespread, but which are expected to grow considerably in the coming years. This can be seen in the case of green hydrogen and electricity-based fuels from solar power in North Africa or the Middle East (see Info box 2, page „Infobox 2:
"Green" hydrogen and synthetic fuels – a special case of electricity
and fuel production“ auf Seite 17).

Unlike other life cycle inventory data, land-use change is not an absolute but a relative value. The "newer" a situation is, the more pronounced the associated land-use change will be, because the existing stock is the value in the denominator. Land-use change will also increase with more dynamic development. This must be taken into account when interpreting the results of land-use change.

When assessing the severity of a chage in land use, another question that arises is the importance of possible reversibility. In the approach presented here, this is reflected to some extent in the gradient of hemeroby between before and after. After all, major jumps from a high degree of hemeroby (e.g. a sealed area) back to a natural forest (low hemeroby) are far more costly than restoring an arable field (moderately high hemeroby). These aspects, which are important for assessing the severity of land-use change, are related to land quality. For the land rucksack, they are measured by assessing hemeroby.

3.2 How to “measure” hemeroby?

3.2.1 The principle of hemeroby classes

In landscape ecology, the division of hemeroby into classes has proven to be a common standard and a useful tool (Sukopp 1972). Depending on the author, between five and ten classes are differentiated.

Seven-part class systems are widespread, as they were first recommended by Klöpffer and Renner (1995) for use in LCA, adopted by Schmitz and Paulini (1999) and further developed by Fehrenbach et al. (2015).

The sorting of land into discrete classes instead of application of a continuous scale does justice to the complexity and multi-layered nature of hemeroby. This cannot be properly expressed with a single parameter (e.g. nitrogen input per unit area or proportion of deadwood). The seven-part classification system has proven its worth, e.g. to allow allocation of common land use types. The first step is to classify the basic land use types of forest, grassland, arable land and various types of settlements with their respective ranges according to the classification system. With reference to original works by Jalas (1955), Sukopp (1976) as well as other authors, the types of use can be classified into (see Table 1, page„The hemeroby class system with indicative allocations of the distribution of different land use types“ auf Seite 17):

- managed forests and timber plantations to classes II to VI,
- (permanent) grassland to classes III to V,
- arable land to classes IV to VI (in special cases class III may also be applicable) and
- mining areas to classes V to VII (mostly class VII).

Settlements are categorically ranked in class VII if they are associated with sealing. However, consideration of unsealed areas in settlements should be more nuanced. In principle, this also applies to fallow and derelict land, the purpose of which lies precisely in its "non-use". Based on the criteria for agricultural land, a set of criteria for fallow and derelict land was also developed.

The classification system has the advantage that characteristic types of use, such as intensively farmed arable land, may usually be assigned to class VI with a high degree of certainty. In contrast, species-rich extensive grassland with a high nature conservation value can be expected in class III. However, such categorical classifications serve as guidance mostly. To determine a specific hemeroby class for an area in use, much stricter criteria are needed, as described in detail below.

One drawback of the division into a total of (only) seven classes are the relatively large jumps between the class boundaries. In individual cases, there may be a small difference between a Class III and Class IV forest. This can lead to unevenness in such individual cases, the influence of which should be discussed in the interpretation of the LCA results if it is conspicuous.

Table 1

The hemeroby class system with indicative allocations of the distribution of different land use types

Hemeroby class	Forest/Forestry	Agriculture		Settlement areas		
I natural	Primary forest, no use					
II	More to less natural forest management					
III		Grassland, extensive, species-rich to intensive management				
IV			Arable land, extensive to intensive management	Derelict land		
V					Mining areas	
VI	Timber plantations					
VII						Sealed surface

Dashed borders show extreme cases, both positive (raw material extraction areas with high nature value potential) and negative (timber plantations with permanent damage to the self-regulating capacity of ecosystems such as eucalyptus plantations).

Reference: own representation 2021, ifeu, extended from (Fehrenbach et al. 2015)

3.2.2 Criteria sets for different forms of land use

How do we perform the actual allocation of land in use to a specific hemeroby class between II and VII? As already mentioned, this is carried out by means of criteria or, more precisely, criteria sets with metrics for determining the intensity of intervention associated with respective human use. Since the type of intervention differs greatly between forest, grassland, arable land or settlement areas, a uniform catalogue for all types of use is not appropriate. What may be a criterion for increased hemeroby in a forest (e.g. fragmentation) may result in lower hemeroby in an agricultural setting (e.g. diversity, structural diversity). For this reason, separate sets of criteria with their own metrics were developed for the different types of land use. A brief explanation of the sets and the underlying concepts follows.

Woodland and forestry

The German terms woodland (Wald) and forestry (Forst) often lack precise definition and clarity. While the term forestry describes a managed forest, the term woodland refers to the ecological community characterised by trees with a mostly closed canopy layer. Since the LCA context is primarily about use, the term commercial forest would be most appropriate here. This would also clearly define natural forests that are not subject to use. For these, no further criteria are needed; they are classified in hemeroby class I. Table 1 illustrates that commercial forestry with different intensities reaching its maximum in timber plantations may be categorised into classes II to VI.

Giegrich and Sturm (1996) were the first to develop a set of criteria for classifying forests into different hemeroby classes. Their approach was based on the guiding principle of forest management that ensures dynamic change as a basic characteristic of all living systems at the species, community and ecosystem level. The goal is a continuous development of the forest soil and forest vegetation largely undisturbed by human intervention. Complete fulfilment of this guiding principle is associated with the lowest level (hemeroby class II) for a managed forest. The criteria catalogue focuses on the relative closeness to nature of (1) the soil, (2) the forest community and (3) the development conditions. These three criteria are operationalised with a total of 20 indicators. The indicators, or metrics, are divided into those that assess the actual state (status quo) of the forest and those that assess active forestry practices.

Overall, the set of criteria and metrics developed by Giegrich and Sturm (1996) is well suited for determining the hemeroby of individual forestry operations. The challenge lies in the scarcity of input data for most of the metrics; data are lacking for forests both in Germany and across Europe. However, it is a key requirement for LCA that life cycle inventory data are available for products such as construction timber, furniture, paper or energy wood. After all, it is usually not known from which forests the raw materials originate. Occasionally the site of origin may be known, and it may also be the aim of a specific LCA to assess the origin of the wood from a particular forest. As a rule, however, it is expected that standard data will be available for the production of wood, as for all processes. For the catalogue of criteria by Giegrich and Sturm (1996), analyses were limited to approximations based on expert assessments.

Even the comprehensive data on forests in Germany, which are now available in the form of the third Federal Forest Inventory (Bundeswaldinventur, BWI-3) (BMEL 2015), do not adequately reflect the metrics of Giegrich and Sturm (1996). Instead, Welle et al. (2018) have developed an alternative forest condition index (Waldzustandsindex, WZI), which is based precisely on the data of the BWI-3 and assesses the overall naturalness of German forests and woodlands. After in-depth examination, the land rucksack study concluded that the WZI also ultimately measures the degree of human intervention on forest ecosystems and thus also refers to hemeroby. This allows a compilation of generic data on the hemeroby of German forests and woodlands. The primary baseline data according to the WZI criteria (Welle et al. 2018) are thus the foundation for the land rucksack criteria, classified in the hemeroby concept according to Fehrenbach et al. (2015). Figure 3 (this page) illustrates this classification. The land rucksack approach also includes additional adjustments to derive specific data for tree species (beech wood, spruce wood, etc.) and to adapt the WZI to individual forestry operations. In both cases, this is done by adding points or deducting points from the average condition of German forests and woodlands in general. The differentiation

Figure 3

Merging the assignment of a hemeroby class according to (Fehrenbach et al. 2015) and the classification scheme of the WZI

Hemeroby class	Brief description for land use type forestry	
I	No intervention. No relevance for the production of goods and services.	
II	Near-natural forest. Very low, near-natural thinning; very low level of intervention; very high secondary benefits.	very good – good
III	Site-specific native forest. Moderate thinning; low intervention intensity; high secondary benefits.	fair
IV	Moderately site-specific native forest. Intensive thinning; considerable intervention intensity; low secondary benefits.	poor
V	Marginally site-specific native forest. Yield-optimising interventions; intensive management with very high intervention intensity; very low secondary benefits.	very poor
VI	Yield optimisation without maintenance of site-specific native community. Maximum intervention intensity; no secondary benefits.	Timber production outside forests has no equivalent in the WZI
VII	Not applicable	

Distance-to-nature potential

Intervention intensity

Reference: own representation, ifeu

according to wood species is vitally important here, as this is known for wood products in many cases and is directly linked to the naturalness or degree of hemeroby of the forest. For beech wood, the appropriate natural species for a quarter of all forested areas in Germany, this results in a lower hemeroby value than for spruce, which is the most common forest tree species but occurs naturally in only 3 % of the forested area (BMEL 2016).

Agricultural land

In contrast to forest ecosystems, the intensity of the intervention on agricultural land cannot be represented as a departure from the natural state without human intervention. In fact, the principle of agriculture itself is human intervention. This applies to arable land as well as grassland and any other type of agricultural use (e.g. orchards, vineyards). A first catalogue of criteria was presented by Fehrenbach (2000). It was based on methods for determining the intensity of intervention in the natural balance as stipulated by the German Federal Nature Conservation Act. Therefore, the aim is the promotion of an agro-ecosystem rich in both structural diversity and species, in which the intervention with nature associated with production processes is limited to the extent necessary for sustainable productivity.

This guiding principle is closely aligned with the concept of High Nature Value Farmlands (HNV Farmland). Alignment with this indicator, which is used to monitor the national biodiversity strategy, is hence important. However, the HNV Farmland concept is not sufficiently differentiated for the task at hand here, as it sets very demanding thresholds, so that the majority of agricultural land (almost all arable land) is not further distinguished (Hünig and Benzler 2017).

Therefore, the preliminary work of Fehrenbach (2000) continues to serve as a basis for the criteria set for agricultural land. Within the framework of the present study, however, the need for further development was recognised and also implemented. Since the original criteria and metrics were based on technical literature from the 1990s, a comprehensive revision to reflect the current state of science was necessary. In the actual (re)definition of the metrics, the key requirement was once again the availability of widely accessible data for each individual metric. These data should also be differentiated in such a way that the cropland of different agricultural products (wheat, maize, rape, etc.) can be mapped with their specific individual hemeroby classifications. Moreover, in this adaptation, the measured variables – with two exceptions – were redesigned to represent measurable units as opposed to qualitative statements.

For instance, the metric "large-scale landscape structure", which describes the degree of field diversity, the interspersion of the landscape with copses and woodland, i.e. richness or monotony, is renamed "diversity in the landscape". It is measured according to the so-called Shannon Evenness Index (SEI), which measures landscape diversity in terms of the number and frequency of land cover types in an area and is available for Europe at regional level in the LUCAS (Land use and land cover survey) database.

The catalogue of Fehrenbach (2000) largely focused on arable land. The assessment of grassland was not sufficiently developed at the time and was thus supplemented by an independent set of criteria-metrics during the update for the land rucksack.

Table 2 (see page„Criteria and metrics of the arable land evaluation system“ auf Seite 20) presents the updated catlogue for arable land. As in the previous versions, this catalogue includes the four criteria diversity of arable flora, structural diversity, soil protection and ma-
terial inputs. Each criterion is defined by two to four metrics, whereas the measured values are divided into five tiers. One point is awarded for the highest tier (indicator of lowest hemeroby), two points for the second tier, and so on (see also Chapter 3.3). The classification of the tiers is based on a comprehensive review of the scientific status quo.

During the project Land rucksacks of goods and services, the data for the classification into the metrics were researched for a large number of agricultural products. Based on these findings, the area under cultivation for the products was classified into a hemeroby class (see also Chapter 4.2).

This comprehensive research was limited to data from Germany. In a first approximation, the results can be transferred to Central Europe, as comparable classifications can be expected here in many metrics. Moreover, the data already reflect a wide range of conditions, since even within Germany there is considerable heterogeneity at the regional level.

This is particularly true for the strongly differing agricultural practices common in the North, South and East of the country.

Considerable additional research is required to create a uniform database at the global level. For the case studies (see Chapter 6), hemeroby classifications were carried out for specific imported goods such as palm oil. Evidently, the hemeroby concept is very suitable for global application overall, but additional data research is still required for many products.

Grassland

The criteria set for grassland is largely similar to that for arable land. Criteria and metrics that do not apply to grassland had to be replaced by appropriate corresponding metrics. For example, there is no tillage or crop rotation (agricultural diversity) for grassland. The criterion soil protection with the metric tillage intensity was changed to management intensity.

Agricultural diversity was replaced by a metric on cutting frequency/grazing. The fact that grassland

Table 2

Criteria and metrics of the arable land evaluation system

Criterion	Metric (updated)	Application and values (1 to 5)
1. Diversity of the arable flora	1. Number of segetal species	Number of segetal species per 100 m²: ›40 | 36–40 | 26–39 | 10–25 | ‹10
	2. Existence of rare species	Number of red list species per 100 m²: (rounded) ›3 | 1–3 | 0,5–0,9 | ›0–‹0,5 | 0
2. Structural diversity	3. Structural elements in the landscape	Percentage of selected ecological priority areas out of total agricultural land: ›3%| 1–3% | 1–1,9% | ›0–›1% | 0%
	4. Field size	Mean field size per crop: ‹1 ha| 1–‹3 ha | 3–‹6 ha | 6–‹9 ha | ›9 ha
	5. Diversity in the landscape	Classified Shannon Evenness Index (SEI) of national agriculture: 5 | 4 | 3 | 2 | 1
3. Soil protection	6a. Intensity of soil disturbance	Descriptive design of the tiers (e.g. “Conservation tillage (without ploughing) without loosening, no heavy machinery” for tier 2.
	6b. Soil compaction due to agricultural machinery use	Diesel consumption from use of agricultural machinery (in L per ha): ‹30 | 30–‹50 | 50–‹70 | 70–‹90 | ›90
	7. Soil cover (cover and land management factor)	Derived from C-factor (cover and land management factor) ‹0,05 | 0,05–0,1 | ›0,1–0,2 | ›0,2–0,3 | ›0,3
	8. Agricultural diversity	Area percentage of field crop of total area in the region: ‹2%| 2–‹5% | 5–‹10% | 10–‹20% | ›20%
4. Material inputs	9. Type of fertilisation	Descriptive design of the tiers (e.g. “Fertilisation only by in-house means (farm manure: exclusively solid), no external input” for tier 1
	10. Intensity of fertilisation	Input of nitrogen fertiliser from mineral fertiliser or farmyard manure (in kg N per ha): 0 | ›0–‹50 | 50–‹75 | 75–‹100 | ›100
	11a. Use of insecticides	Descriptive design of the tiers (e.g. “exclusively biological, biotechnical and physical measures” for tier 2).
	11b. Plant protections measures (excl. insecticides)	Application of plant protection agents and fortifiers, in treatment index (TI): TI=0, preventive measures| TI=0, biological measures | ›0–‹2 | 2–‹4 | ›4

Reference: own representation, ifeu

often performs much better than arable land in the other metrics, which are largely identical to the latter, shows that grassland in principle is associated with lower hemeroby. For example, the use of plant protection measures is generally lower on grassland than on arable land.

Please note that grassland in the land rucksack is defined as permanent grassland. Annual or temporary grasslands are classified as crops derived from arable farming in this approach.

Mining

The development and extraction of fossil, mineral and metallic raw materials take place in opencast mining for deposits near the surface and in underground mining for deep deposits. While the former represent obvious intervention with the land surface, the latter are associated with extended spoil heaps causing an impact on the land. Furthermore, raw material extraction usually requires additional infrastructure. Until now, these areas have always been categorically classified as Class VII when applying the hemeroby method. The reason for this was the total alteration of the area by completely removing or covering the natural surface.

However, this approach is considered too sweeping because it equates small-scale extraction measures such as limestone quarries and gravel pits with extensive opencast mining operations. This is particularly true if high-quality habitats for rare animal and plant species are created through subsequent use and in some cases already during the extraction phase. For this reason, a separate set of criteria for mining and raw material extraction has been developed. This should enable differentiation between different geological conditions or biotope characteristics and include mining duration and intensity.

Land occupation and hemeroby are calculated by considering the total of all areas currently used for mining in a given year. In addition to the area under extraction (opencast mining) and the waste rock piles (underground mining as well as opencast mining), this includes the footprint of mobile and stationary extraction equipment, operating buildings, processing plants and roadways.

Table 3 (this page) provides the criteria and metrics focusing on the intensity of the intervention, the potential natural development and the permanence of the intervention. The classification into hemeroby

Table 3

Criteria and metrics of the mining area evaluation system

Criterion	Metric	Implementation and tiers (1 to 3)
1: Severity of the intervention	Capacity of mining equipment	in m³ extracted materials per hour ‹100| 100–1000 | ›1000
	Annual extraction rate per deposit	in tonnes per annum ‹100,000| 100,000–2 million | ›2 million
	Water use	none | irrigation | groundwater lowering
	Tilt as a barrier to natural succession	none | ‹50% | › 50%
2: Biotope development	Biotope value according to Küpfer 2016; Vogel / Breunig 2005	III | II | I
	Formation of small biotopes (structural richness) and potential for succession	present | – | absent due to immediate regeneration
	Quality of natural development without human intervention	High-quality | regular | no development
	Importance for the biotope network	Very high | medium | low
3: Duration of the intervention	Deposition of hazardous materials on site	none | low | high acidity and heavy metal pollution
	Regeneration potential (Method Küpfer 2016; Vogel / Breunig 2005)	Biotope value after 25 years Class V | Class IV | Class III

Reference: own representation, ifeu

classes determined from these metrics ranges from class V to class VII. The metrics were specifically defined according to the requirement that data for the classification of individual raw materials are readily available. Thus, the respective hemeroby may be determined, in particular for various mineral raw materials including sand, gravel, limestone and other types of natural stone.

Settlement areas

Settlements include a variety of different types of land that may be partly sealed and partly unsealed. However, even the unsealed areas are strongly influenced by human activity. While sealed surfaces, such as buildings and traffic areas, are generally assigned to hemeroby class VII, unsealed surfaces require a more differentiated approach with their own evaluation system of criteria and metrics.

These include, in particular, fallow or derelict areas that are kept clear for specific reasons. Due to the analogy between such derelict urban land and arable land, the evaluation systems for derelict land and arable land are very similar. Differences exist, e.g. in the size of the area (Metric 4); here, as with grassland, the "the larger the better" rating applies to derelict land for areas rich in vegetation. In contrast, in areas with little vegetation, the evaluation is reversed and analogous to arable land.

3.3 Assigning hemeroby classes

As introduced above, several criteria with a total of up to 20 metrics are usually used to determine the hemeroby class of an area. The large number of individual results from these metrics serves to reflect the diversity of factors governing naturalness at a specific site as comprehensively as possible, and thus safeguards the scientific foundation of the assignment to a hemeroby level. This is intended to guarantee a reliable classification.

Moreover, the large number of individual metric results allows aggregation to be as simple as possible and to be used without weightings and complex algorithms. Each individual result counts equally. As seen in the introduction of the criteria sets, the result of a metric is a value on a scale from 1 to 5 (for agricultural areas) or from 1 to 3 (for mining areas). Tier 1 corresponds to the highest and Tier 5 or 3 to the lowest performance value of the respective metric. For the assignment of a metric to Tier 1, 1 point is awarded; for Tier 2, 2 points are awarded, and so on. The arithmetic mean is calculated from the individual values of all metrics of a criterion. An overall mean is derived from the means of the criteria.

This final result after consideration of all the metrics falls between 1 and 5 and is subsequently assigned to the hemeroby classes II to V for forest systems or to the hemeroby classes III to VI for agricultural land according to the methodology shown in Table 1 (see page 18). For raw material extraction, the classification ranges from the hemeroby classes V to VII.

A tiered assessment accepts that quantitative data from specific sites may give the impression of imbalance due to the step function. In practice, however, estimates and assessments based on broad assumptions occur much more frequently than data compiled specifically for the purpose of an LCA. This is then again compatible with the allocation of points according to tiered groups, which incidentally also allows the consideration of descriptive aspects. The large number of metrics is intended to compensate for such uncertainties.

3.4 Characterisation model for the impact assessment

The impact assessment summarises life cycle inventory results in one impact category. Consequently, individual land use results, differentiated according to hemeroby classes, are summarised into one indicator value. In continuity with the UBA assessment method (Schmitz and Paulini 1999), the impact category is referred to as natural land use. But how are 3.5 m² of class II, 7.1 m² of class III and 1.2 m² of class VII added into a total?

In the case of climate change, with Global Warming Potential as the indicator, 1 kg of methane (CH_4) has 29 times the impact potential of 1 kg of carbon dioxide (CO_2). Since it is common practice to normalise greenhouse gases to equivalents CO_2, 1 kg of methane is thus equivalent to 29 kg of CO_2. All greenhouse gases can be added up in this unit. The factor 29 is also referred to as the characterisation factor.

For the land rucksack, the following question arises: How does a square metre of hemeroby class VII compare to a square metre of another hemeroby class? How "weighty", i.e. how grave is a square metre of hemeroby class VII in comparison with a square metre of hemeroby class VI or any other hemeroby class? Unlike the radiation physics of gaseous molecules, there is no definitive quantifiable environmental effect mechanism for this. However, the endpoints can be clearly determined: they range from zero (no hemeroby, intact undisturbed nature, i.e. class I) to one (complete sealing, i.e. class VII).

Since LCA explores negative environmental impacts, the worst case – class VII – is selected as the reference point, i.e. the other classes are converted into area equivalents of class VII with a corresponding characterisation factor. The so-called artificial area equivalent, or aa-eq, is defined as the unit. Analogous to the Global Warming Potential in climate change, the indiscator value for the impact category of natural land use is referred to as the "distance-to-nature potential" (DNP).

The key question remains: Which characterisation model should be used to determine the characterisation factors for the DNP? As already mentioned, science does not provide a clearly quantifiable calculation basis for the measure of hemeroby. The LCA standard ISO 14044:2016 provides the opportunity in section 4.4.5 to include comparable empirical observations for the justification of the impact indicators. The underlying values and assumptions must be documented.

Fehrenbach et al. (2015) proposed a characterisation model defined by two key assumptions:

1. the determination of the minimum range between the characterisation factors of the land classes; and

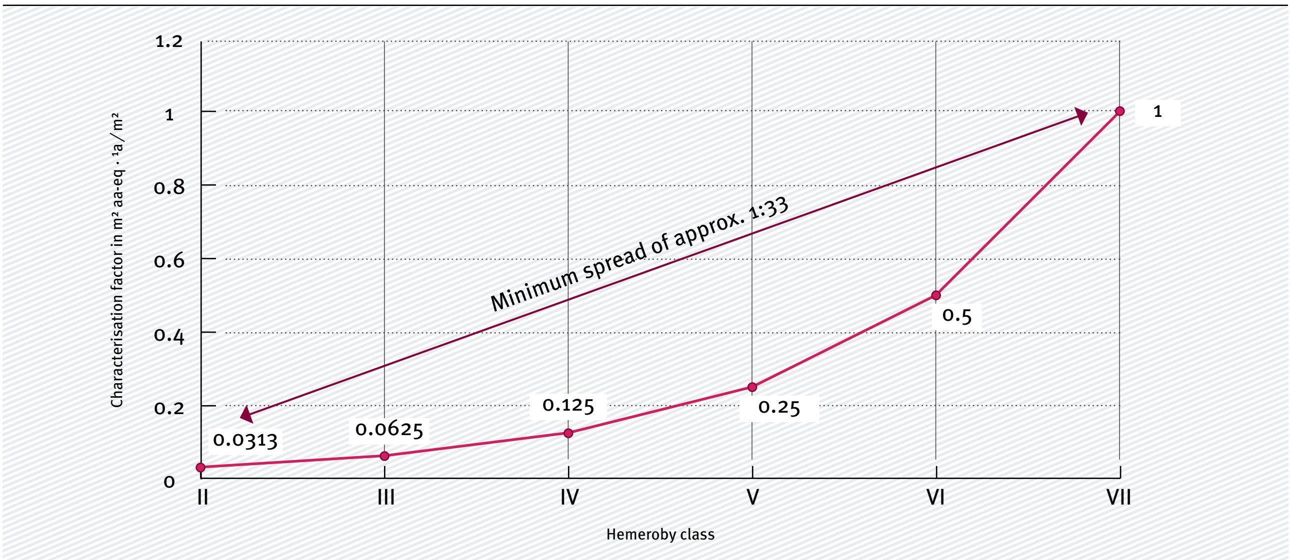
2. he determination of the distances between the classes.

Since class I – no hemeroby – equals zero, the question of the minimum range is about the distance, i.e. the factor, between classes II and VII. In other words: how many m² of class II "outweigh" 1 m² of class VII? Since class II, as a near-natural commercial forest, is far removed from a sealed area VII, the distance must be sufficiently great. How great it must be at a minimum can be explored with the following mental experiment. If the entire land area of the world were used with the least possible human intervention (i.e. Class II), the "negative" environmental impact of this total area should not be quantified as greater than that resulting from the totality of the area currently used with the highest hemeroby (Class VII). Since about 3% of the global land area can be classified as Class VII[4], the factor between Class II and VI must come to at least 0.03 to 1 (or 1 to 33). A lower factor would lead to absurd results, in which the global increase in sealed or devastated areas could lead to a global decrease in hemeroby. This must be avoided.

4 According to UNEP, 2% of the global land surface was sealed in 2012 (UNEP 2014). Assuming a further one percent of devastated land, this results in 3 % as Class VII land; for comparison: in the EU, 8.8 % is sealed (land used for residential, commercial and industrial purposes) (Eurostat 2011).

Figure 4

Correlation between characterisation factors and individual hemeroby classes



Reference: own representation, ifeu

Following this rationale, the factor 33 between hemeroby class VII and II is defined as adequate. Since this is a minimum value, it cannot be ruled out that arguments for a further increase of this range will be found as a result of further analyses.

Next, how are the distances between the classes to be defined in the following step? Again, it is a challenge to justify a purely scientific function. Aspects that play a role here are, for instance, time spans of development from one class to the next. However, a consistent approach suggests the use of the same factor from class to class. Thus, the transition from class VII to class VI would be as large as the transition from class III to class II. By application of a factor of 2 or 0.5 from class to class, the total factor of 33 is achieved almost exactly across the six classes from II to VII: 2 x 2 x 2 x 2 x 2 = 25 = 32.

Based on this, the values shown in Figure 4 (see page 24) result as characterisation factors for the individual hemeroby classes. In absolute factors, the difference between class II and class III appears much smaller than between class VI and class VII. However, this is a question of perspective and is in line with empirical evidence: looking from a sealed area (VII) first at an arable area (VI) and then at two different forest areas – a near-natural (II) and a fairly natural forest (III) - the distance to the arable area is large and to the forests again much larger. However, the difference between the two forest areas (although actually a factor of 2) is hardly noticeable from the perspective of the sealed area. Thus, the exponential function is also supported by empirical perception.

4

Data

4 Data – the key to LCA

4.1 Which data are required, which are available?

An applicable method requires data that are readily available. These may be found at two different levels:

1. Ideally, complete life cycle inventory data sets are available for the key variables land occupa tion, land transformation and hemeroby, e.g. in the form of a database.
2. Alternatively, data to create life cycle inventory data sets for the variables above are available and may be used at a reasonable cost and effort.

If the second level of availability cannot be provided, the method is unlikely to be successful. Introduction of the method would require primary data collection, which could be expected and reasonable for specific data in the context of an LCA. However, if primary data collection must be carried out for the entire life cycle inventory data sets, the application is bound to fail.

The initial state of data availability for the land rucksack was outlined in chapter 2.1. A number of database systems are available that provide product-related land occupation data. However, only ecoinvent, which also includes data on land transformation, offers a broad coverage of life cycle inventory data. However, a more in-depth analysis of this database revealed that there are considerable gaps for the goals and requirements associated with the land rucksack. The shortcomings can be summarised as follows:

- The data originate from isolated research or individual literature sources and are usually not very current (time horizons are often at least ten years in the past, often date further back).
- There is no integration with national database systems, which means that it is not possible to update the data using current data, e.g. from national statistics or other official sources.
- The concept of land transformation is not consistent with the approach chosen here.

The classification of land into use classes according to the so-called CORINE classes does provide indications for a possible allocation to a hemeroby class[5]. Overall, however, the classification is too coarse and requires specific allocation, interpretation and further information for such, which is not apparent from the database itself. Overall, the data on hemeroby in the databases are thus insufficient. Evidently, ecoinvent may serve as an essential data source for numerous products here. However, this source is not sufficient to meet all the goals of the land rucksack. It must be supplemented by others, especially those that allow for timely updating of the data sets. DESTATIS in particular would be an important source for this.

5 Fehrenbach et al. (2019) translated existing ecoinvent data categories into hemeroby classes.

Table 4

Origin of source data and conversion to input data for the land rucksack

Source data	Conversion to input data land rucksack
Land occupation ▸ Primary data from surveys or dedicated studies ▸ Data from official statistics (e.g. Destatis, FAO) ▸ Data from LCA databases (e.g. ecoinvent)	Land occupation factors for products and services
Land transformation ▸ Primary data from surveys or dedicated studies ▸ Data from official statistics (e.g. Destatis, FAO) ▸ Data from LCA databases (e.g. ecoinvent)	Land transformation factors for products and services
Hemeroby ▸ Data for individual metrics from surveys or dedicated studies	Hemeroby classes per product or service, for land occupation and original condition in the case of land transformation

Reference: own representation, ifeu

Table 4 (this page) shows the initial data for land occupation, land transformation and hemeroby from which lifecycle inventory data for the land rucksack can be derived or calculated.

In principle, every form of production involves a form of land occupation. Every product system includes a large number of interconnected process modules. The land rucksack of a product is therefore composed of the land occupations of all these linked process modules. The question of which data should be included in the calculation of a land rucksack depends on the desired degree of aggregation of the process modules. The focus is initially always on the key process module. In the case of agricultural cultivation processes, this is the cropland needed for the product. However, this is only a section of a larger product system, in which the upstream chains (land that is used, for example, in the production of fertilisers) and the processing up to a finished product (land for the provision of, for example, electricity) must also be included. In addition, land occupation also arises from infrastructure (e.g. roads or factories). Figure 5 (this page) biodiesel product system as an example.

As for all other impact categories in LCA, the overall complexity must be kept to a minimum. Data sets such as those developed in this study focus primarily on disaggregation at the level of the key process modules. For common products with a high level of process integration, such as electricity from solar energy or the average mix from the electricity grid, we provide data sets on their respective land rucksacks.

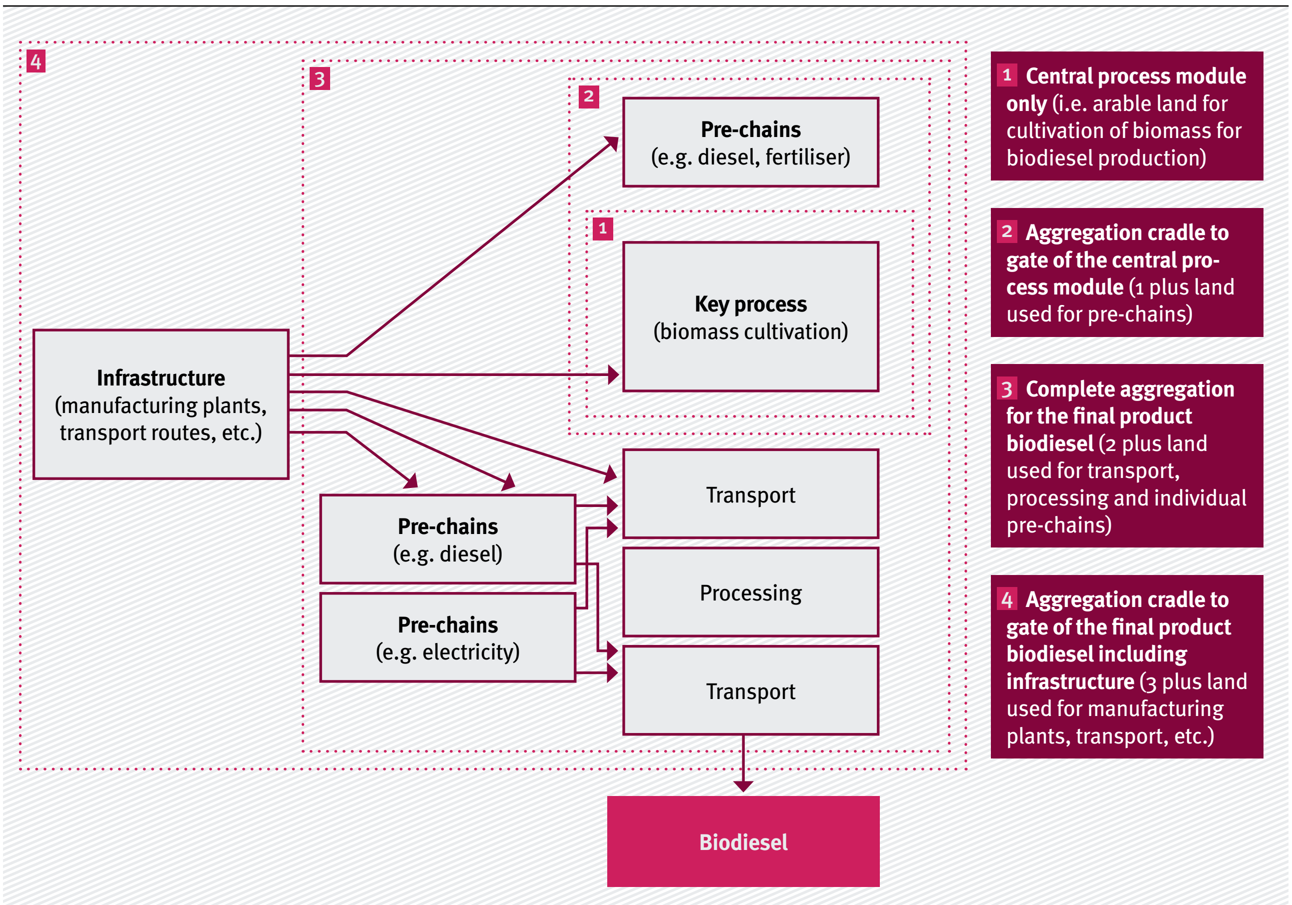
4.2 Which data does the land rucksack provide?

The study Land rucksacks of goods and services aimed to complete a basic methodological frame-

Figure 5

Different levels of aggregation of life cycle inventory data for products or product systems

Product system – aggregation level (Example biodiesel production)



Reference: own representation, ifeu

work and to produce comprehensive set of life cycle inventory data. First and foremost, these data were required for the modelling of the case studies (see Chapter 6). In fact, the resulting novel database extends much further. However, it does not represent a complete database for all conceivable products and services. Such a database could be developed in future work.

Data sets on the cultivation of biomass were compiled for as many relevant agricultural and wood products as possible. For the agricultural products, data sets were also created for conventional and organic cultivation as well as for "unspecified" cultivation. The spatial reference is Germany. An extension to the European framework can be made using corresponding statistical data for land occupation and land transformation. A transfer of the data on hemeroby to the European level would require further analysis.

Data sets for wood products differentiated according to the main timber species are also based on general data for Germany. There is not yet a common scientific consensus on the question of dedicated timber certificates (e.g. FSC) and whether independent data sets should be created for these. A transfer to wood products from other countries (especially Nordic countries, Eastern Europe, including Russia, the USA and Canada, plantation wood from South America or Southeast Asia, such as wood from tropical forests) is possible, but was not carried out here.

In contrast, most fossil raw materials - at least those relevant for the German market – are represented at the global level. Among raw materials associated with considerable land use, there is still a data gap for Canadian tar sands.

Mineral raw materials are well represented with data for gravel, sand and natural stones in case of production in Germany. Ore mining is primarily modelled with global data from ecoinvent.

The life cycle inventory data for electricity from wind and solar energy was compiled in great detail including data from the most recent studies. Unlike in most of the above-mentioned product segments, very dynamic developments are under way here. This concerns both new construction (which leads to comparatively high values for land transformation) and an increase in efficiency (which leads to a reduction in land occupation per kWh). In addition to onshore wind energy and ground-mounted photovoltaics in Germany, solar electricity generation in the Middle East and North Africa (MENA) region was included in the case study exploring "green hydrogen" and electricity-based fuels (PtL).

Other infrastructure areas such as operational facilities (production plants, power plants) and transmission systems (pipelines, electricity transmission grids) are already integrated in the energy systems. Transport is also of key importance. Thus, life cycle inventory data were compiled for essential transport services (passenger and freight transport).

Table 5 (see page 29) summarises the products and services for which this study developed input data.

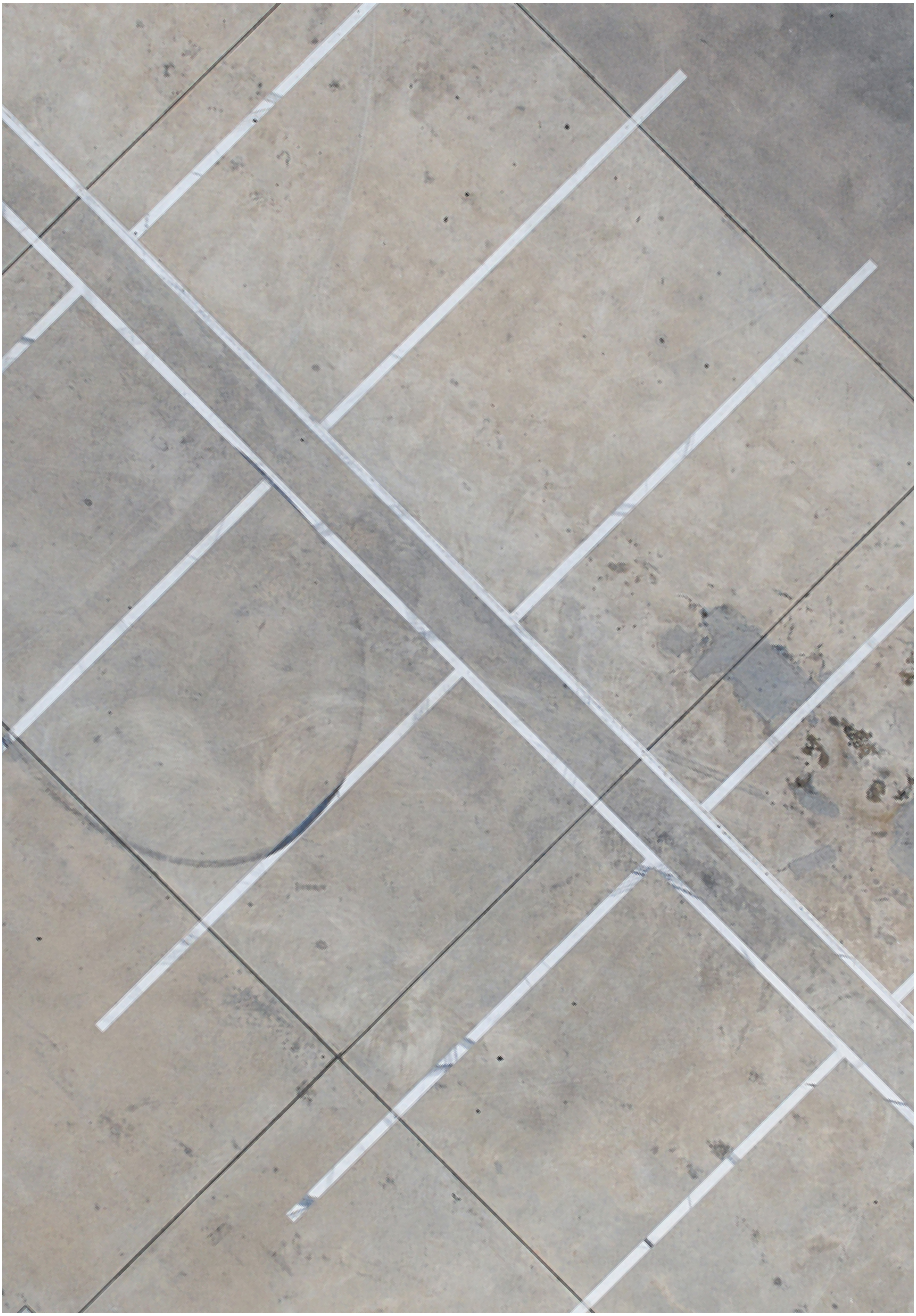
Table 5

Products and services included in the land rucksack database

Wood and agricultural products [a] (biomass)	Mineral and fossil raw materials	Non-biobased renewable energies	Transport (passenger/freight)
▸ Wood, unspecified ▸ Beech wood ▸ Oak wood ▸ Other hardwood, native species ▸ Spruce wood ▸ Scots pine wood ▸ Silver fir wood ▸ European larch wood ▸ Douglas fir wood	▸ Construction sand ▸ Construction gravel ▸ Crushed natural stones ▸ Limestone and dolomite ▸ Loam and brick clay ▸ Gypsum and anhydride stone ▸ Pumice, trass and tuff ▸ Iron ore (46 %) ▸ Iron ore (63 %)	▸ Onshore wind energy (German mix of open countryside and forest) ▸ Wind energy open countryside (Germany) ▸ Wind energy forest (Germany) ▸ Ground-mounted photovoltaic power plant (Germany) ▸ Solar thermal power plant (MENA) ▸ Ground-mounted photovoltaic power plant (MENA)	▸ Passenger car ▸ Motorbike ▸ Moped ▸ City bus ▸ Long-distance bus ▸ Coach ▸ Road, urban and underground transport ▸ Local passenger rail transport (railway) ▸ Long-distance passenger rail transport (railway)
▸ Fodder beet ▸ Potatoes ▸ Grain maize ▸ Silage maize ▸ Summer field bean ▸ Summer peas ▸ Spring barley ▸ Spring oats ▸ Spring wheat ▸ Sunflower ▸ Winter barley ▸ Winter rape ▸ Winter rye ▸ Winter wheat ▸ Sugar beet ▸ Pasture cuttings, unspecified ▸ Pasture forage, unspecified ▸ Grassland, extensive ▸ Grassland, organic farming ▸ Palm oil (Indonesia, Malaysia)	▸ Lignite ▸ Bituminous coal (mix Germany) ▸ Bituminous coal Russia (opencast and underground) ▸ Bituminous coal USA (opencast mining) ▸ Bituminous coal Colombia (opencast and underground) ▸ Bituminous coal Australia (opencast mining) ▸ Bituminous coal South Africa (opencast mining) ▸ Crude oil (mix use in Germany) ▸ Crude oil Russia (onshore) ▸ Crude oil Nigeria (onshore) ▸ Natural gas (mix Germany)		▸ Heavy commercial vehicles (HDV) ▸ Light commercial vehicles (LDV) ▸ Freight train

[a] For crops, data sets for conventional, organic and unspecified cultivation are provided.

Reference: own representation, ifeu



5

Interpretation

5 Interpretation – how to draw conclusions?

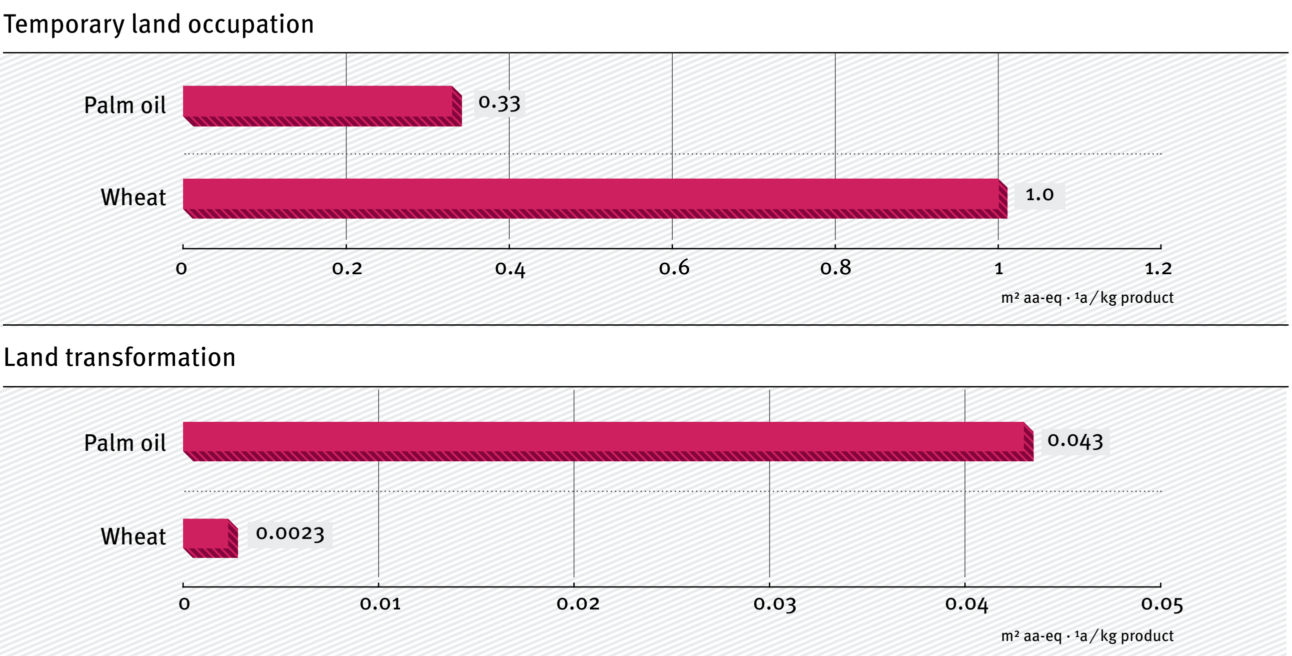
The land rucksack study provides a methodological approach and a set of life cycle inventory datasets for application of the method during impact assessment. If the method is applied in an individual LCA, it fits into the overall set of various impact categories, and the results of the land rucksack are available for consideration in line with climate change, acidification, human toxicity, etc. Please note that the land rucksack distinguishes between two types of impacts: temporary land occupation and land transformation. Incidentally, this is in line with the UNEP-SETAC life cycle assessment initiative, which also differentiates between occupation and transformation.

Even though both impacts are each expressed with the indicator distance-to-nature potential (DNP), they are separate entities and carry different messages, which is reflected in the different units. Both types of impacts are therefore considered separately and provide two separate pieces of information for evaluation within the impact category of natural land use. Please note that there is just as little scientific basis for a merging into an aggregated land indicator as there would be for an aggregation of climate change and acidification. The use of two or more indicators for one impact category is not unusual. An example or analogy may be found in the Product Environment Footprint (PEF), which divides a category such as human toxicity into "cancer effects" and "non-cancer effects".

At the impact assessment level, the two indicators therefore remain separate. Figure 6 (this page) shows one possibility for a joint graphical representation of land occupation and land transformation using the example of wheat (Germany) and palm oil (Indonesia). The question of the different orders of magnitude can also be solved by a suitable reference value with the process of normalisation. It serves to render the different results of the impact categories comparable and to prepare them for the analysis (interpretation). The ISO standard defines normalisation as the calculation of the magnitude of the impact indicator values in relation to the reference information, i.e. normali-

Figure 6

Combined presentation of land occupation and land transformation modelling wheat (Germany) and palm oil (Indonesia)



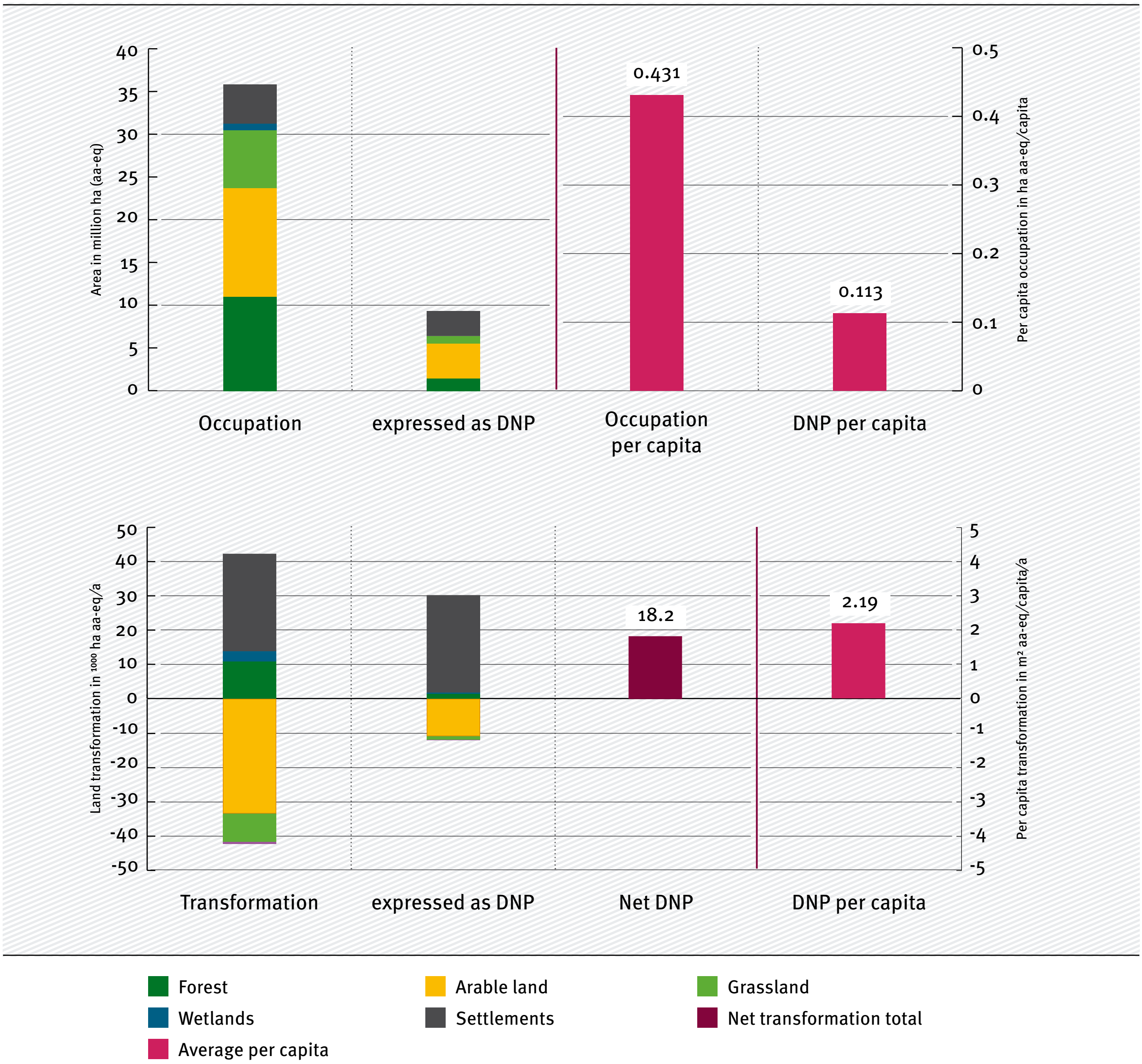
Reference: own representation, ifeu

sation provides context to characterised results by relating results to a reference. As a rule, per capita impacts such as the average greenhouse gas emissions of a resident of Germany, Europe or the world serve as such. These factors are also referred to as averages-per-capita (APC). For greenhouse gas emissions, an APC for a resident of Germany is calculated to be 9.8 tonnes per capita per year.

For uncharacterised land occupation and land-use change, Germany-wide or Europe-wide data may be found in national statistics. For land transformation in particular, data from the national inventory reports on the UN Framework Convention on Climate Change (NIR) serve as a basis. No official source can provide the corresponding data for the hemeroby of the land used. These were therefore collected or estimated over the course of this study. Based on approx. 35.8 million ha and a population of 83 million, the per capita occupation is 4,310 m². Figure 7a illustrates land composition and its representation as the distance-to-nature potential (DNP of 9.4 million ha aa-eq). This results in a DNP of 1,130 m2 aa-eq per capita.

Figure 7

Total DNP of land area in Germany; top for land occupancy, bottom for land transformation; left displayed in absolute total area, right converted to average impact per capita.



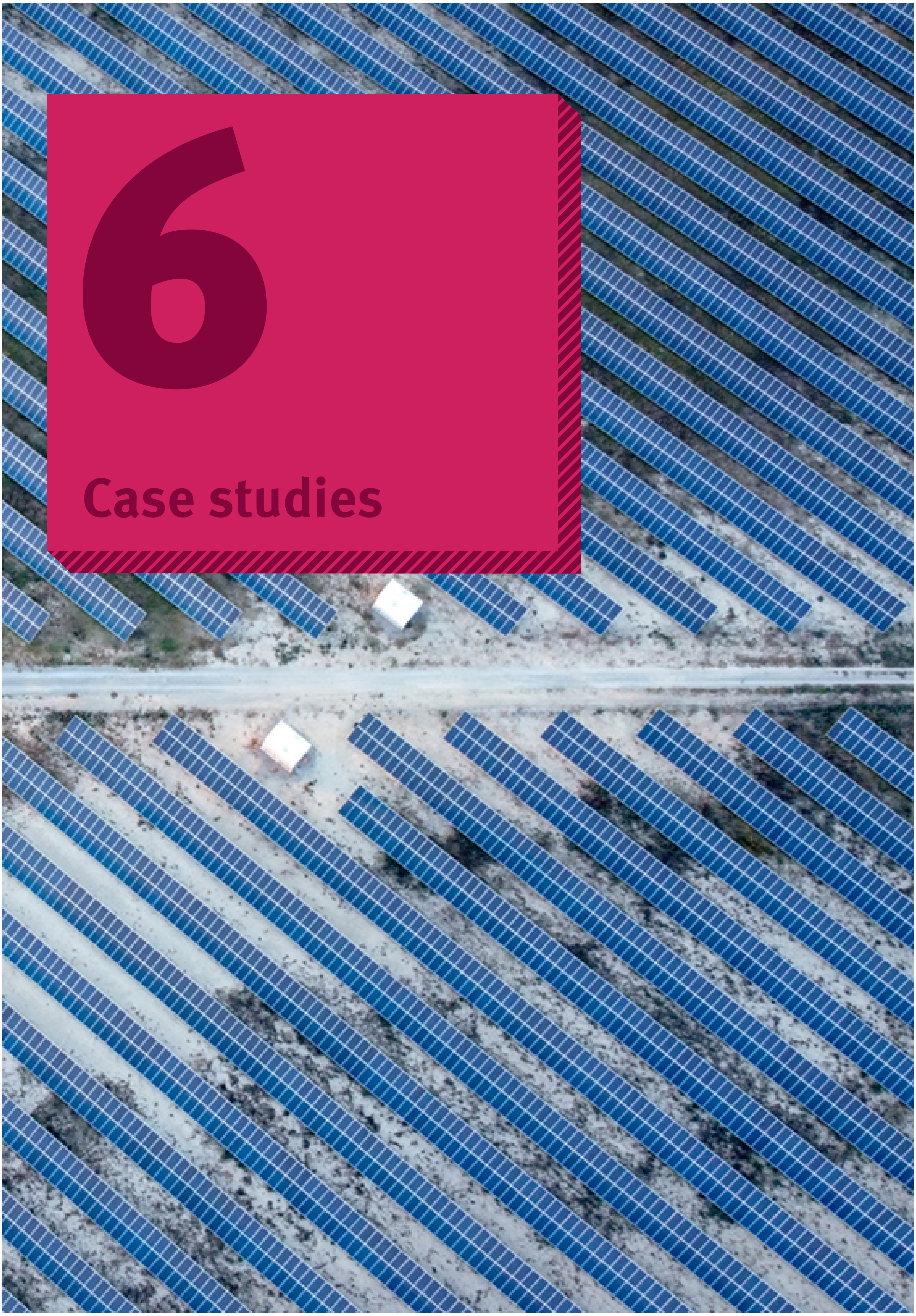
Reference: own representation, ifeu

Figure 7b (this page) presents the data on land transformation. Positive values represent types of use that are associated with an annual net increase, whereas negative values represent those that show a net decrease. Without characterisation, the land-use change balance is zero (bars on the left). The balance shows impacts only after characterisation as the DNP, which is this case is positive, i.e. ongoing land transformation in Germany leads to an overall increase in hemeroby (third bar from the left as the balance of the positive and negative contributions in the second bar group). The amount is 18,200 ha aa-eq per year. Converted as APC, this results in approx. 2.2 m² aa-eq per capita and year.

Thus, two independent indicators for natural land use can be included in the LCA process. They are treated in the same way as the indicators of the other impact categories. However, the case of land use reveals a weakness in the usual approach of the national APC for normalisation: the domestic balance is not identical with the causal balance. Distributing all greenhouse gas emissions released in Germany among the German population ignores the emissions caused abroad through imports of raw materials and consumer goods. On the other hand, local industry also produces on a large scale for export. Given the high total of emissions, this blurring of impact categories such as climate change is generally accepted. Since the standardisation is less about precise factors than about a scale-based orientation aid, this is also acceptable. However, for land use, it can be assumed that the discrepancy between domestic balance and consumption is greater. We import significantly more land than we occupy for export purposes. In all likelihood, the difference in land transformation is even more pronounced. This takes place at a comparatively low level in Germany. In contrast, many imported goods such as soy meal, palm oil and metal ores are associated with considerable land transformation.

Which conclusions may be drawn for the land rucksack method? The land-use APC for Germany are very likely an underestimate of actual consumption. For imported products that are associated with a high degree of land occupation or land transformation in particular, the normalisation can thus produce very high values. This can certainly provide useful assistance for the analysis, but must also be adequately reflected in the interpretation at the end.

Keyword interpretation – in addition to the aspects discussed above, the following thoughts should be taken into account when evaluating land rucksacks in LCA: Land transformation differs in principle from all other life cycle inventory variables - including land occupation - in that it expresses a difference between a state “before” and “after”. Thus, it is essentially not an absolute but a relative variable. It is also decisive how the changes (e.g. increase in an activity) relate to the actual situation (the current scope of the activity). It was already pointed out in Chapter 3.1.2 that activities that are comparatively new and undergoing dynamic increase in land occupation are associated with high land transformation per se. In contrast, activities that are already established and in widespread use lead to correspondingly low land transformation. As a result, products that have seen little representation on the market so far and now require new land for their growth are associated with a relatively high land transformation. When interpreting the results, this should be taken into account for the cases in which the effect is particularly striking. The discussion of LCA results should therefore take into account, depending on the specifics of the analysis, whether an activity is associated with high land transformation values only because of its innovative character (large increase at a small level) or because of a massive increase in area (large increase at an already larger level).



6

Case studies

6 Land rucksack case studies

Three of the case studies modelled in the land rucksack project are presented in detail below, plus a brief overview of the results of the fourth case study. They illustrate the broad applicability of the land rucksack method across many forms of land use. The spectrum of case studies explored shows that the method is suitable for a range of complex situations and delivers robust results.

For example, the case study on electricity production in Germany shows how the various energy carriers (coal, gas, nuclear, wind, solar, biomass, etc.) are represented in detail, plus the average production mix, and explores the land rucksack of renewable electricity options.

The case study on passenger transport serves as an example of a service, i.e. a 100-kilometre journey in a compact class passenger car. In addition to the fossil energy source diesel, biofuels (B7, also differentiated into rapeseed and palm oil) are considered here as well as electricity in the form of a battery-electric vehicle, integrating data from the first case study on electricity.

Another energy source for propulsion included in the analysis are electricity-based fuels (PtL)[6] . An independent case study on PtL and green hydrogen was carried out (see info box 2). The results are presented in line with the overall modelling of passenger transport.

The last case study explores construction materials. The land rucksacks of structural load-bearing elements made of a range of construction materials (glued laminated timber, steel, reinforced concrete) are assessed. In this case study, land use arising from forestry is compared with mining for gravel, lime and iron ore.

6.1 Electricity production in Germany

It is no secret that electricity flows from the socket – but what happens to the land needed to provide it? What about the land occupation and land transformation associated with electricity production?
Do the land rucksacks of the different available energy sources differ? These questions are examined in the case study on electricity production in Germany.

6 PtL: power-to-liquid

Electricity in Germany is provided from various energy sources. Here, the land occupation and land transformation associated with the provision of 1 MWh of electricity are considered. In addition, the Distance-to-nature potential for the different energy sources is determined. The following options were included in the case study:

- Electricity from the German electricity grid, as an average production mix in 2019,
- Electricity from an average mix of renewable energy (RE), according to the percentage shares in the average production mix in 2019,
- Electricity from the individual renewable energy sources of solid biomass, biogas, ground-mounted photovoltaics and onshore wind energy considering all technologies separately.

For the analysis of electricity production, a framework must be defined, the so-called system boundary. In the case study, both the raw material extraction of the energy sources (fossil raw materials, uranium ore, solid biomass (wood) and biomass for biogas production) and the respective processing infrastructure are included in the calculation of the land rucksack. The electricity production infrastructure includes thermal power plants (conversion of fossil or biogenic primary energy sources), plants for direct conversion of wind and solar as well as transmission grids (facilities for transporting electricity, transformation). Installations on existing structures (e.g. roof-top photovoltaics) do not lead to additional land occupation. Since waterbodies have not been included in the methodology to date, offshore wind energy plants and hydropower plants are not considered.

The average production mix for electricity in Germany includes the energy sources lignite, bituminous coal, oil, natural gas, nuclear power, wind power, photovoltaics, biogas, solid biofuels, waste incineration and hydropower. Land occupation data on the raw materials and the various infrastructures (power plants, transmission grids, etc.) were aggregated.

Land occupation outside Germany, e.g. coal mining or natural gas extraction and transport (pipelines) in the countries from which the feedstocks are imported, also play a role. The average RE electricity mix is derived from the shares in the average production mix.

For the use of solid biomass for energy purposes, land occupation only plays a role in the case of direct wood extraction from the forest or for the by-products of wood processing (sawmill residues and other industrial residues). Waste wood and landscape conservation cuttings are not taken into account. Thus, only 25 % of the wood used in large-scale combustion plants are associated with land use.

Considering land occupation for biogas requires a differentiation according to the various biogas substrates. These include maize silage, whole plant silage from grain, grass silage, other renewable raw materials, liquid manure and biowaste.

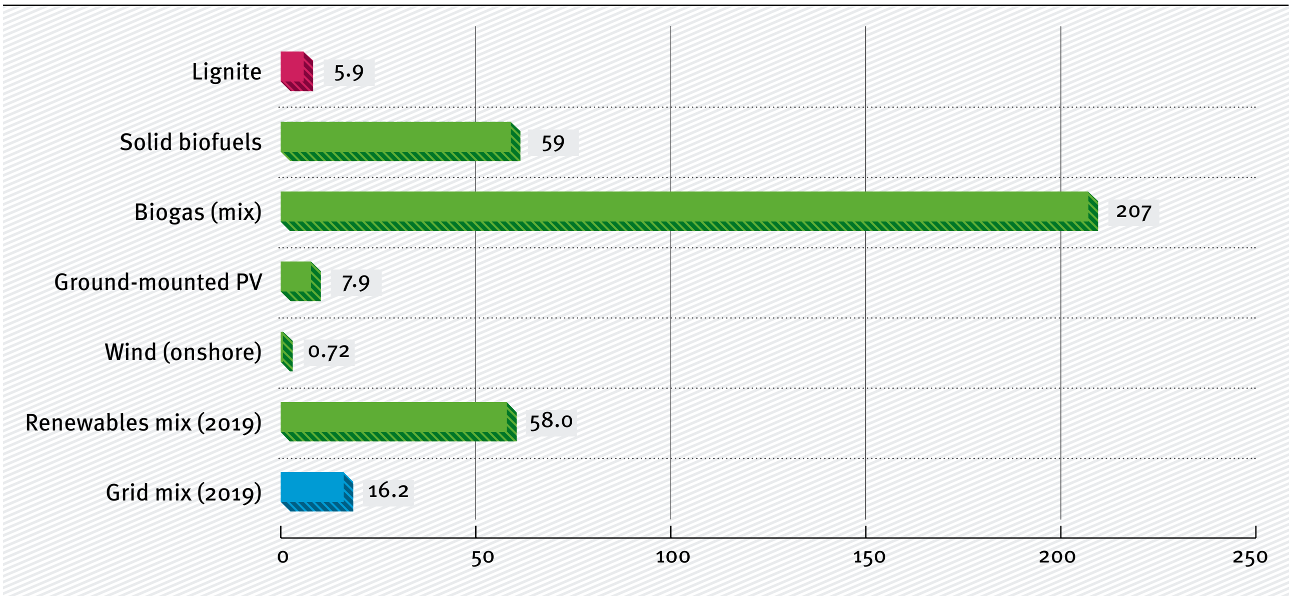
If solely land occupation is considered, 1 MWh of electricity from biogas requires most land, followed by electricity from solid biomass, whose land use intensity is similarly high. The mean RE electricity mix occupies about one third of the area of pure biogas. The land use intensities of the medium electricity mix, ground-mounted photovoltaics and especially wind energy are comparatively low.

The results for the distance-to-nature potential of the land occupation of the individual energy sources or the average mixes are shown in Figure 8 (this pages).

Electricity from biogas is associated with the highest distance-to-nature potential of land occupation, fol-

Figure 8

Distance-to-nature potential of the land occupation associated with different energy carriers used for electricity production in Germany



DNP of the specific land occupation in m² aa-eq · ¹a per MWh electricity

Reference: own representation, ifeu

lowed by electricity from solid biomass combustion – however, the distance-to-nature potential of solid biomass is only about a quarter of that of biogas. Clearly, the distance-to-nature of forests is significantly lower than that of agricultural land. Due to the high share of electricity from biogas in the average RE electricity mix, the distance-to-nature potential for renewables is almost as high as for solid biomass and also higher than the average German electricity mix.

In contrast, ground-mounted photovoltaics and wind energy are associated with low distance-to-nature potentials. The distance-to-nature potential of the land occupation associated with lignite is lower than that of photovoltaics. The energy density of lignite and the thickness of the seams mined result in significantly more kilowatt hours generated per square metre than from a PV installation. This includes the long period of time during which the opencast mining area cannot be used for other purposes. It is also taken into account that the opencast mine is classified in hemeroby class VII and the PV installations fall between hemeroby classes V and VI.

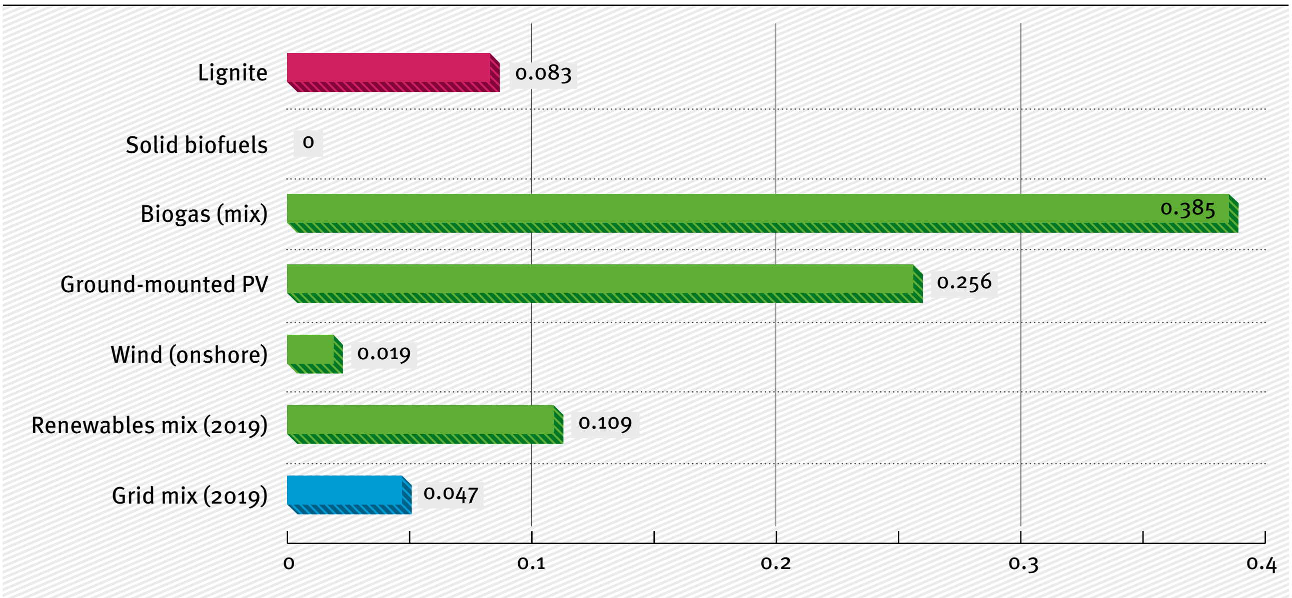
A look at the distance-to-nature potential of land transformation (Figure 9, this page) shows that electricity from biogas has the greatest influence here, followed by electricity from ground-mounted photovoltaics. The latter ranks ahead of the other energy sources due
to the dynamic expansion over the last few years despite the comparatively low hemeroby change. Fossil fuels, on the other hand, have been established for quite some time and thus show little relative growth. Consequently, they are also associated with low distance-to-nature potentials due to changes in land use.

Lignite ranks below the average RE electricity mix in the individual analysis, but clearly above the German electricity mix. Please note that land transformation only considers the relative increase and the associated change in the hemeroby class compared to the previous use. The extent to which the observed land transformation is reversible or irreversible is irrelevant here.

Overall, it is evident that the use of cultivated biomass, whether from agriculture or forestry, is fundamentally land-intensive, involves land transformation and is associated with a high distance-to-nature potential. The land rucksacks of the individual energy sources and average mixes in Germany are dominated by the provision of raw materials, while the processing infrastructure is secondary.

Figure 9

Distance-to-nature potential of the land transformation associated with different energy carriers used for electricity production in Germany



DNP of the specific land transformation in m² aa-eq per MWh electricity

Reference: own representation, ifeu

Extrapolation of these specific data to the current total electricity consumption of about 570 TWh and normalisation of the DNP results of land occupation and land transformation with the per capita averages introduced in Chapter 5, Figure 7 (see page 34), reveals the following results:

- 2.75 million hectares or just under 1 million hectares aa-eq are occupied for electricity consumption with the current electricity mix. This represents 7.7 % of the total land area of Germany or 10 % of the total DNP associated with land occupation in Germany.
- Land transformation amounts to 2,780 hectares aa-eq per year. This is 15 % of the total DNP associated with land transformation in Germany.

The role of electricity generation in land occupation and land transformation is thus quite relevant.

- To supply the entire electricity consumption with the current RE mix, the DNP for this would increase to 37 % of the total occupation. The biogas share is primarily responsible here. If the entire German electricity consumption were supplied by the current mix of biogas electricity, its DNP would be 130 % of the current land occupation. The values for land transformation are similarly high for both energy sources (mixes).

- In contrast, if the entire electricity consumption were to be supplied by ground-mounted photovoltaics, the current DNP occupation of electricity would be halved to 5 %. However, there is a marked difference for the DNP of land transformation. A complete supply with ground-mounted PV would correspond to about 80 % of the current total change. With onshore wind energy, the impacts would be significantly lower: only 0.5 % (one thirtieth of the current occupation by electricity production) would be occupied by wind energy. The land transformation through exclusive onshore wind energy would increase the total DNP impact by 6 %.

The aim of these figures is to render the distance-to-nature potential accessible as a parameter for LCA, similar other impact categories. For example, the results in the impact category climate change are likely to be significantly different: A complete supply of the electricity demand by PV electricity would reduce the load of the electricity sector in the total load on climate change to about 1 %. In contrast, a supply exclusively with lignite-based electricity would approx. double German greenhouse gas emissions. In LCA, an overall conclusion including findings for all impact categories would then be drawn.

Again, please note that the land rucksack only considers impacts on the land itself. Process-related impacts on nature conservation and landscape protection, e.g. from wind turbines that impact on bird protection or through extensive groundwater subsidence through opencast mining, are not taken into account here.

6.2 Passenger transport energy

Without mobility, engaging in public life and society is very difficult. Efficient and sustainable solutions for transport are therefore essential. But which form of propulsion technology has a particularly high impact on land use? Do the land rucksacks of different fuels or electricity sources differ? What are the distance-to-nature potentials of land occupation and land transformation associated with the different propulsion energies? The case study of propulsion energy in passenger transport sheds light on various options.

The case study explored the provision of propulsion energy for 100 passenger-kilometres (pkm) for a compact class vehicle with different types of propulsion, i.e. both combustion technologies and purely battery-electric propulsion, as well as the special case of electricity-based fuel, in which synthetic fuel produced from electricity is used in a combustion engine (see info box 2). The following drive energies were part of the analysis:

- Diesel (fossil),

- Diesel (B7, including blending of up to 7 % biodiesel),

- Pure biodiesel (consisting of 47 % waste vegetable oil, 28 % rapeseed oil and 21 % palm oil),

- electricity-based fuel (PtL) derived from solar power in the MENA region and

- battery-electric charge with renewable energy (modelled both as the average RE mix and wind energy and ground-mounted PV supplying 50 % each).

The scope for passenger transport includes land occupation and land transformation for the provision of the respective propulsion energies and land occupation for traffic infrastructure. Vehicle production is not considered. Charging stations and petrol stations are also excluded because their land use impacts are assumed to be small.

For the combustion technologies, the extent of land occupation is determined by the share and type of biomass used, i.e. the biomass influences the land use intensity of a certain propulsion energy. Rapeseed methyl ester (RME) from rapeseed oil is associated with the highest land occupation due to comparatively low yields. For palm oil methyl ester (PME) from palm oil, the yields per area are higher, so palm oil has an advantage over rapeseed. The current average

Infobox 2:
"Green" hydrogen and synthetic fuels – a special case of electricity and fuel production

Hydrogen is likely to play a key role in the energy supply of the future, i.e. successful climate protection is out of reach without a shift from fossil feedstocks to renewable energies. In principle, the use of hydrogen is not a novelty, it is commonly used in refinery processes and in the chemical industry. In the future, this use is to be increased considerably, but energy is needed for the production of hydrogen. So-called green hydrogen is produced when the entire production process is completed with renewable energies.

Due to the energy balance, renewable electricity should always be used directly and without any diversions such as hydrogen production. However, according to current forecasts, hydrogen is needed as a fuel for a range of sectors, e.g. in the chemical and steel industries as well as in aviation and shipping and, to a certain extent, in freight transport. Two-thirds of future hydrogen demand will probably be met by imports. Regardless of where the production of green hydrogen takes place, industrial production will have impacts on the land.

The land rucksack project considered land used for the production of green hydrogen through the use of solar thermal energy in the so-called MENA region (Middle East & North Africa). For the production of green hydrogen or synthetic fuel, a series of chemical processes are connected in sequence. In the first step, solar energy is applied to produce electricity. The MENA region is well suited because it receives plenty of direct solar radiation. However, this electricity could also be generated with ground-mounted photovoltaic systems in Germany. In the second step, the solar electricity is used in the processes of electrolysis of water, water treatment (desalination of seawater in MENA), CO_2 capture (from ambient air) and power-to-liquid (Fischer-Tropsch synthesis). The analysis compared the land use of the different technologies, estimating the areas of the respective plants. The construction of plants and infrastructure as well as transport routes and transmission networks were not taken into account.

The land rucksack for the production of green hydrogen (by electrolysis of water with renewable electricity) and synthetic liquid fuel (PtL) produced from it differs depending on the production site.

- Land occupation: In the MENA region, only about half the land is needed due to the higher radiation intensity. If the distance-to-nature potential of the land occupation is taken into account, the two locations converge, since even in light of the different ecological regions, the hemeroby of the land of a plant in the MENA region is greater than that of PV plants with extensive vegetation under and between the modules, which is common in Germany.

- The Distance-to-nature potential of land transformation is higher in the MENA region than in Germany as the German land is already in use, while the MENA land was in a natural state before it was converted for hydrogen or PtL production.

- The land rucksack of hydrogen and PtL is determined by the energy demand of the production processes electrolysis and Fischer-Tropsch synthesis. In contrast, CO_2 extraction from the air and water treatment processes are almost negligible.

The comparison of the land rucksacks at the two production sites shows that the distance-to-nature potential of land occupation and land transformation can be quite opposite. Since future dynamic growth is expected in the MENA region, this comparison should not be used as definitive for decision-making.

biodiesel mix overall requires less than half the land area of rapeseed, as it contains a high proportion of waste vegetable oils to which no land occupation is attributed. Synthetic fuel derived from solar power in the MENA region is even less land-intensive. Finally, fossil diesel is associated with very low land occupation, so that even B7, with an energy share of approx. 6.5 % of biodiesel, shows very low land occupation.

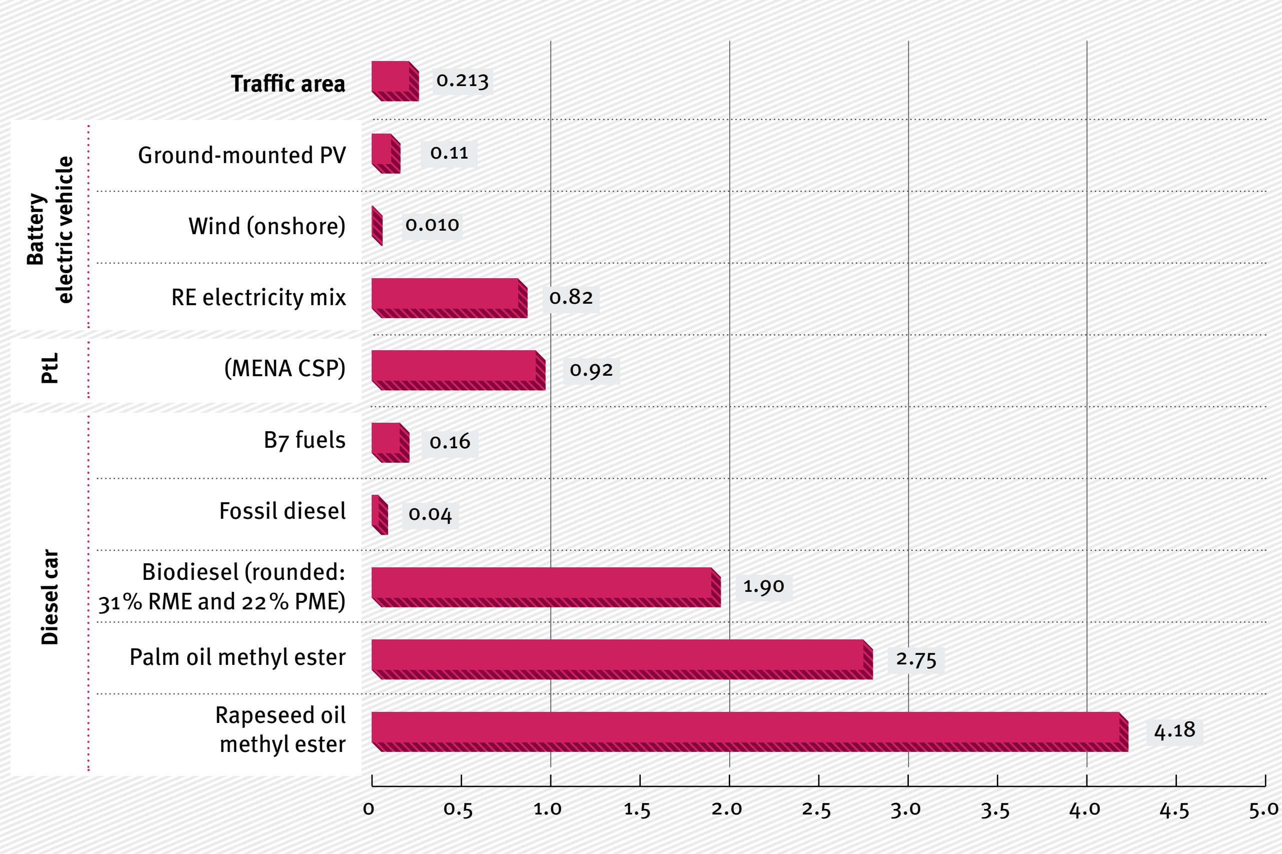
Similar to the internal combustion engines, the land occupation of battery-electric drives also differs depending on the proportion of biomass used in electricity production. A journey of 100 km with a battery-electric car occupies the most land if the average RE mix is assumed for battery charging, which includes electricity from biogas and solid biomass. Due to the biomass components, this journey is also more land-intensive than with a diesel car powered by B7. However, with electricity from onshore wind turbines or ground-mounted photovoltaics, the occupation is lower than with a B7 diesel car, especially for wind energy.

The distance-to-nature potential of land occupation is illustrated in Figure 10 (this page). Rapeseed cultivation is not only land-intensive, but also associated with the highest distance-to-nature potential, followed by palm oil, which scores slightly better because it is a perennial crop. The distance-to-nature potential of biodiesel falls between the two oil crops. The results for the distance-to-nature of synthetic fuel produced with electricity in the MENA region and the RE mix are lower. Ground-mounted photovoltaics and wind energy are associated with very low distance-to-nature potentials, so that driving an electric car powered by solar or wind energy is preferable to all other options. A slightly different picture emerges for the distance-to-nature potential associated with land transformation (Figure 11, see page 43).

Synthetic fuel produced with solar power in the MENA region is associated with the highest distance-to-nature potential of land transformation because of the current large-scale construction of plants and thus,

Figure 10

Distance-to-nature potential of the land occupation associated with different propulsion technologies used in passenger transport

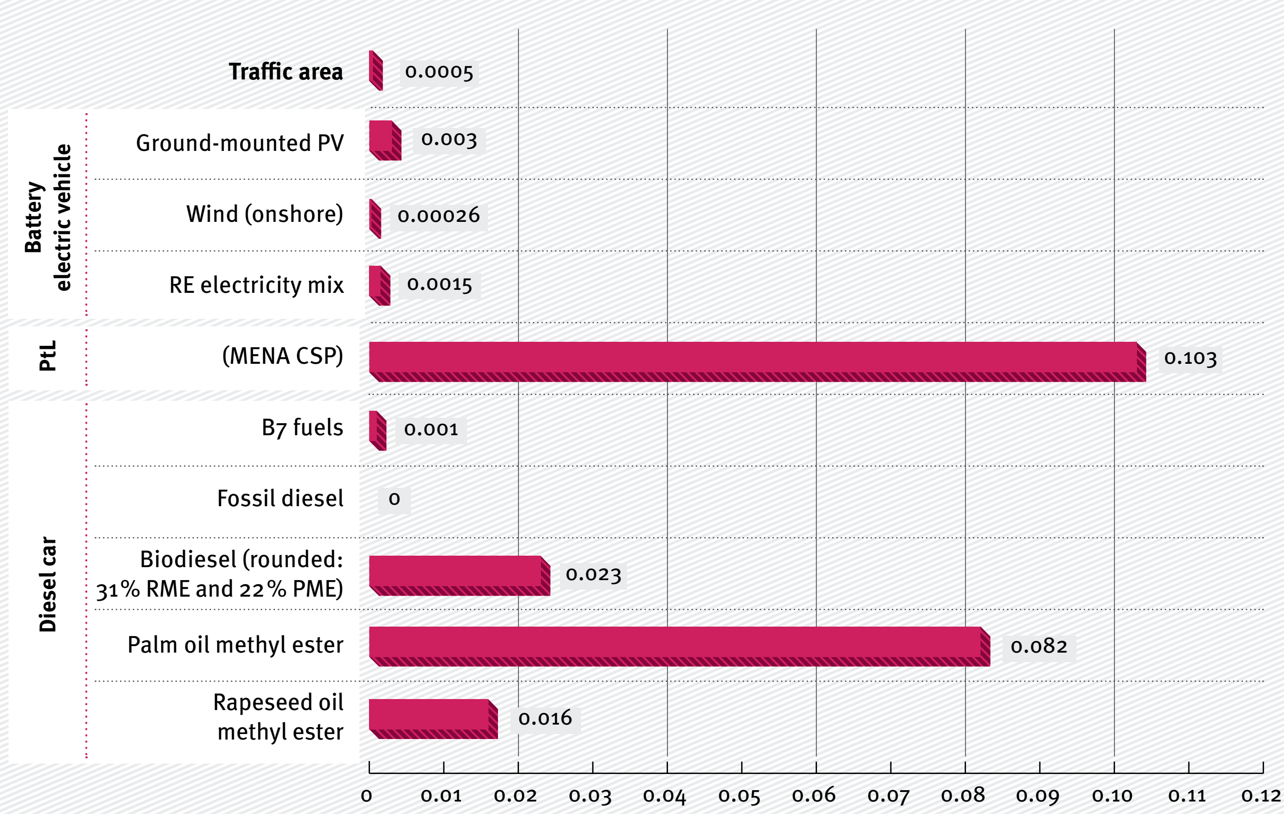


Distance-to-nature potential in m² aa-eq · 1a per 100 km driven

Reference: own representation, ifeu

Figure 11

Distance-to-nature potential of the land transformation associated with different propulsion technologies used in passenger transport



Land transformation in m² aa-eq per 100 km driven

Reference: own representation, ifeu

land conversion. The consequence is a conversion from the initial natural state to intensive use. The distance-to-nature potential of land transformation for palm oil is also high. Furthermore, unlike land occupation alone, it clearly exceeds that of rapeseed. This reflects the high deforestation rates in the countries where palm oil is produced.

The results illustrate that both aspects of the land rucksack, i.e. land occupation and land transformation, play an essential role. Often, analogous statements emerge for both components. However, high-yield cultivated biomass, the production of which involves considerable intervention on the land, is a counterexample and reveals the complexity of each individual land use scenario.

Similar to the electricity case study, extrapolation to the current total mileage of approx. 630 billion kilometres by passenger cars in Germany and consideration of the DNP results of land occupation and land transformation with subsequent standardisation with the per capita averages introduced in Chapter 5, Figure 7 (see page 34), results in the following:

- The total mileage - assuming diesel B7 as the current standard – is associated with an occupation of approx. 330,000 hectares or 100,000 hectares aa-eq. This equals 0.9 % of the German land area or 1.1 % of the total DNP due to land occupation in Germany.

The shares of passenger transport, currently still dominated by fossil fuels, in occupation and land transformation are thus comparatively small. With the alternative options, however, it will increase, as the following scenarios show:

- With a complete switch to biofuels from bioenergy crops[7] , the DNP would rise to 29 %, assuming rapeseed diesel. Palm oil diesel would be slightly lower

7 Hypothetically, because the legal requirements limit the eligibility of biofuels from food and animal feed to minimum quotas precisely because of the land use issue.

at 18 % due to the higher yield. These findings are reversed for land transformation: a pure rapeseed diesel input would increase the total DNP by 20 %. However, if German cars operated only with palm oil diesel, the total DNP would increase by 290 %, i.e. almost quadruple.

- A complete switch to e-mobility with an RE electricity mix would results in an additional occupation of approx. 5 %. Assuming only photovoltaic electricity or only wind power, these values slip below 1 %. In the case of land transformation, the RE electricity mix also reaches 5 %, whereas wind power is associated with 1 %. Photovoltaic electricity, on the other hand, would increase the DNP by 12 %.

- In the scenario modelling electricity-based fuels (PtL) from solar power in the MENA region, the additional occupation for a complete supply of passenger transport would be 6 %, which does not seem particularly high, but would still be around eight times higher than driving with photovoltaic electricity only. In any case, the land transformation is very high at 3.5 times the current total DNP. This shows that this technology is not only land-intensive, but will also lead to the occupation of large areas of new land that were previously unused or used for other purposes.

The extremes found for land transformation in this case study clearly show that any interpretation must always be approached with caution. Palm oil diesel production as well as electricity for PtL takes place outside Germany. The comparatively low current domestic factor for land-use change is one reason for the very high values of well over 100 % in some cases. If, on the other hand, the entire fuel sector would be switched to domestic biofuel, a massive increase in land-use change in Germany would be the consequence. The case study would thus have a direct influence on the normalisation factors, which ultimately results circular reasoning. It should therefore be emphasised that the results of the normalisation should only ever be understood as an orientation or guidance, not as actual values.

6.3 Construction materials

Every construction project has an impact on the environment, not least because of the sealing of the surface on which it is built. But what role does the choice of construction materials play for land occupation? Do the land rucksacks of different source materials differ? Do the distance-to-nature potentials of land occupation and land transformation change depending on which construction materials are used? The construction materials case study examines different materials used for building.

Specifically, the distance-to-nature potentials of land occupation and land transformation associated with structural load-bearing elements (hall beams) made of different construction materials were compared here. The required load capacity of all options was defined as follows: 10 m span and a dead load of 11.6 kN/m (not including the dead weight of the beam).

The following options were included, whose respective structural specifications are defined by the relevant DIN norms:

- Timber hall beam: forest area harvested for timber supply; the glulam beam is produced from either spruce or fir.

- Steel I-beam: area devastated for iron ore mining, as well as the area for the energy required for steel production (German electricity mix; lignite mining simplified for coke).

- Reinforced concrete beam: area devastated for iron ore mining, as well as the area for the energy needed for steel production (German electricity mix; lignite, simplified for fossil fuels as well as for the coke used); area of aggregates (sand, gravel) needed for concrete, quarry area for quarrying the limestone needed for cement (simplified) and the energy needed for cement production (German electricity mix, lignite mining).

The construction materials case study compared the land use associated with the materials used (forest area of the harvested timber, ore mining, limestone mining, etc.). For better comparability with the other case studies, the particularly land-intensive parts of the manufacturing processes were also considered (e.g. energy for steel and cement production). The following aspects were excluded from the model: machinery etc. for the provision of wood as well as for the extraction of rock/provision of aggregates, auxiliary and operating materials, transport and infrastructure, energy costs associated with construction, energy costs for wood processing, hot rolling of steel or casting of concrete, life cycle and end-of-life considerations of the products with regard to the allocation of steel scrap, cascade use of wood, etc.

The construction materials considered here are made of very different materials, so the impact on the land also varies considerably depending on the material used. The two hall beams made of wood require significantly more land than those made of steel and reinforced concrete. The fir hall beam has the highest land intensity; the reinforced concrete hall beam achieves the lowest.

If the distance-to-nature potential of the land occupation is included (Figure 12, this page), the outcome changes. Here, spruce wood has the highest distance-to-nature potential of all four construction materials, because spruce, unlike fir, is mostly non-natural. In consequence, fir wood is associated with a lower hemeroby, which offsets higher land intensity. For both wood-based hall beams, the distance-to-nature potential results from raw material extraction. In contrast, for the steel-based hall beams, the electricity in the manufacturing process is key. Hall beams made of steel have a higher distance-to-nature potential for land occupation than those made of reinforced concrete, which score best in the comparison based on occupation only. As soon as a broader spectrum of impact categories is considered, however, different results can be expected. Reinforced concrete is therefore not preferable to timber in principle.

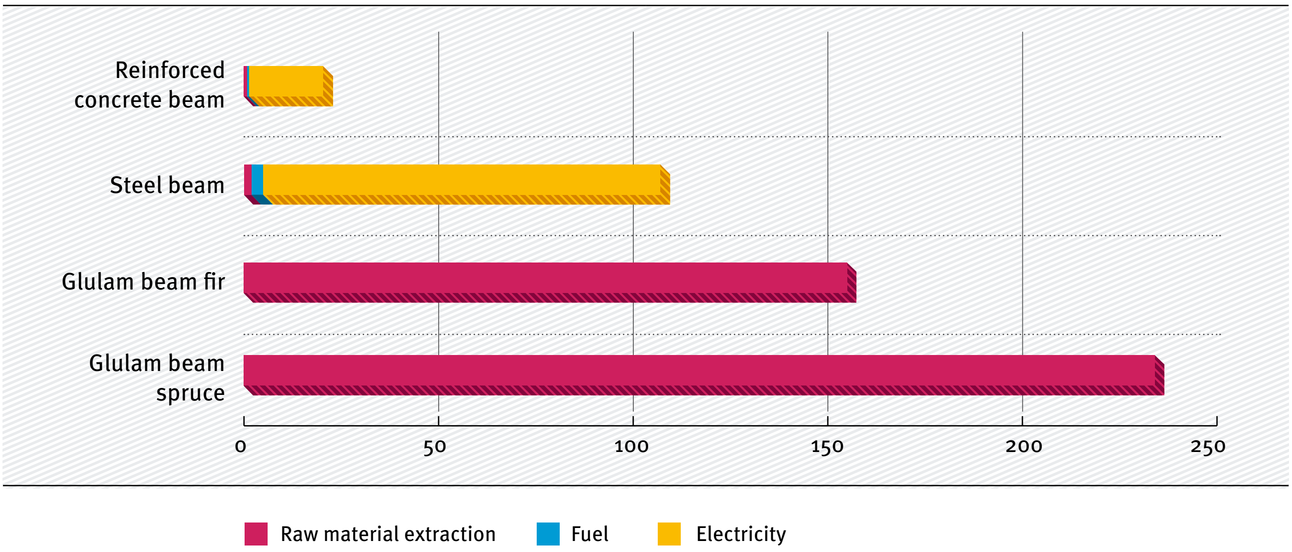
The distance-to-nature potential of the land transformation (Figure 13, see page 46) approaches the land in question from a different angle, so that the results of the analysed construction materials change notably. For the two systems made of wood, the land transformation is assumed to be zero, as the overall land use is maintained through selective wood harvesting. The key factor here is the electricity demand during production, which is why the steel hall beam is associated with a particularly high impact.

Overall, the case study exploring construction materials also shows that both components of land use, occupation and transformation, provide essential information that should not be discounted in the decision for a particular construction material.

Once again, the results for both indicators are normalised in the final step. Unlike the other two examples, normalisation is not based on the total volume of the construction industry, but only on the supporting structure of a model hall building with 100 beams with a 10 m span each. The normalisation for this is carried out with the average-per-capita data described in Chapter 5.

Figure 12

Distance-to-nature potential (DNP) of the land occupation associated with different hall beams

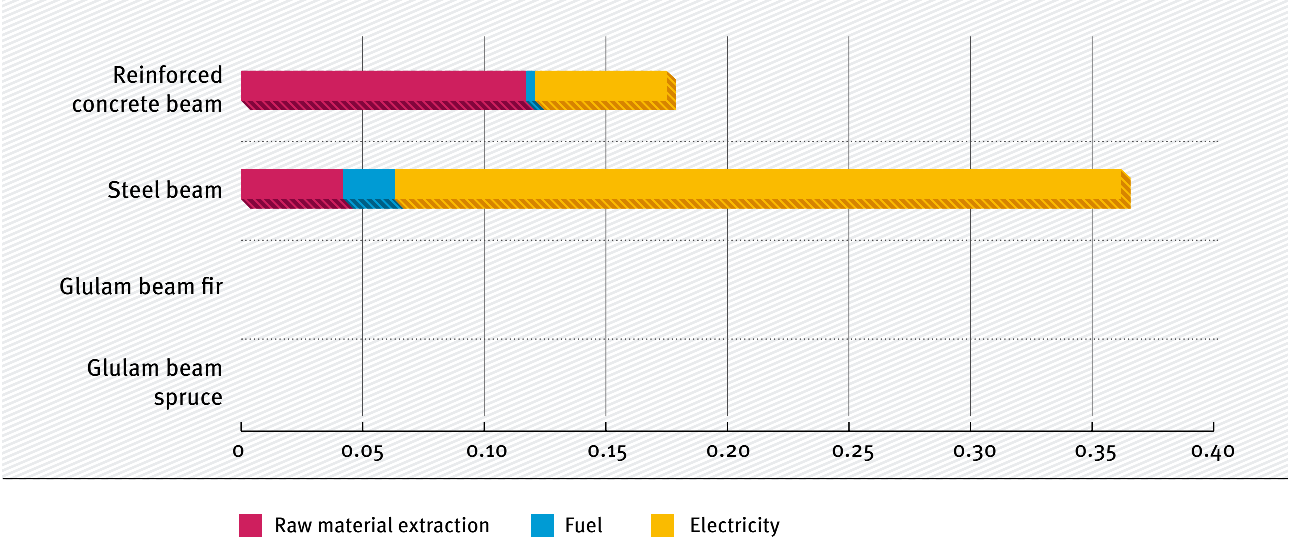


DNP in m² aa-eq · 1a per beam

Reference: own representation, ifeu

Figure 13

Distance-to-nature potential (DNP) of the land transformation associated with different hall beams

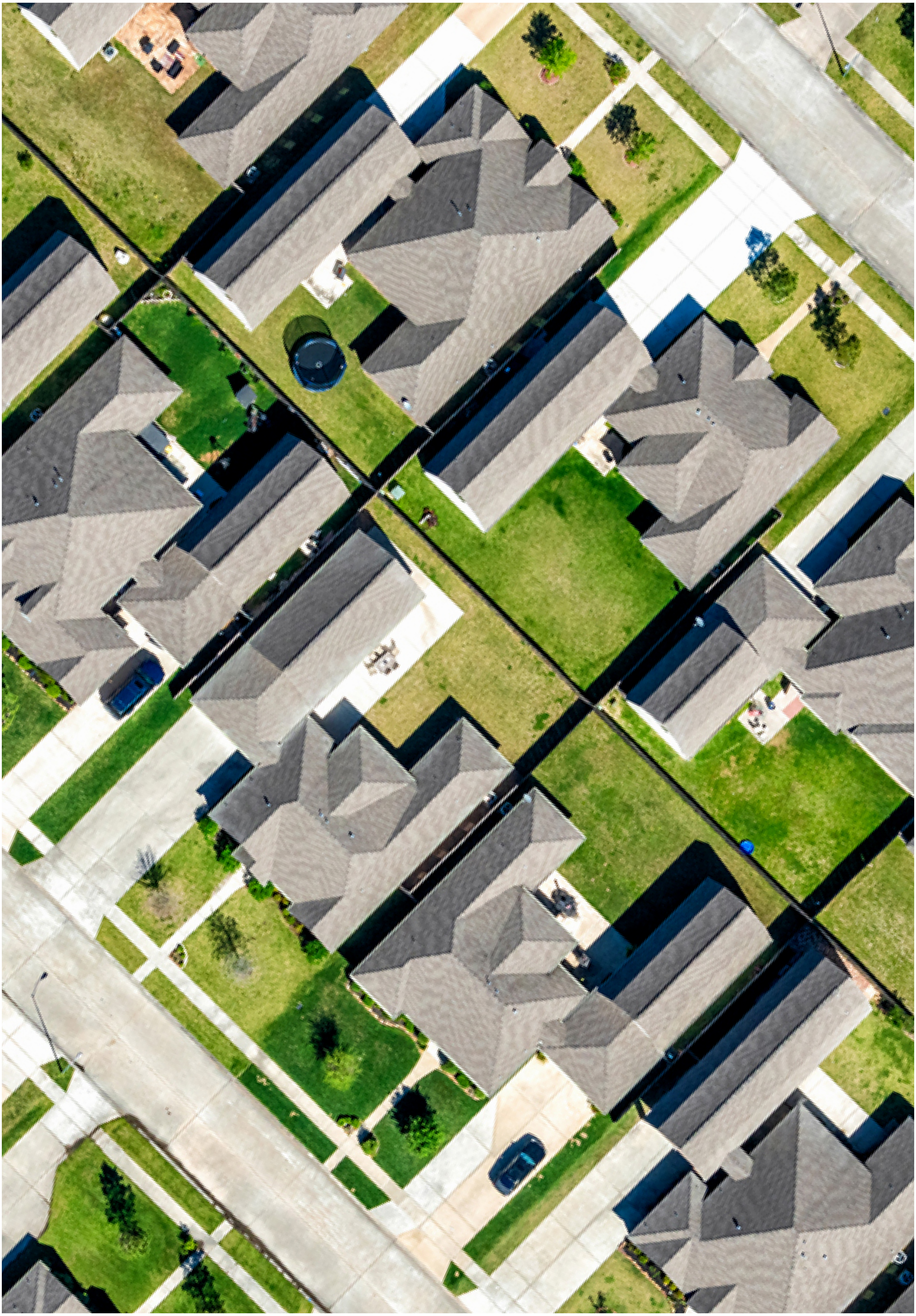


DNP in m² aa-eq per beam

Reference: own representation, ifeu

As a result, the land occupation for the structure made of spruce wood corresponds to 26 APC, the structures made of fir wood and steel each require 9 APC, whereas the hall built with reinforced concrete beams achieves 2 APC. The average-per-capita calculated for land transformation are 8 APC for reinforced concrete and 17 APC for steel. The land transformation of zero for wood is also associated with 0 APC for this construction material. Thus, the two opposing indicators fall into similar orders of magnitude for their respective specific contribution. At the same time, the normalisation underlines that the fir structure has an advantage not only over spruce, but also over the steel beam. And since there is no clear advantage between the steel beam and the reinforced concrete beam in view of the APC results, the fir structure emerges as the most favourable when considering the respective land rucksacks[8].

8 NB: For this type of evaluation, the APC are comparable, but adding the APC of land occupation and land transformation is not appropriate, as the two indicators can be unequal in terms of environmental impact.



7

Present and future

7 Present and future

The land rucksack study developed a comprehensive methodology and database to consider land use in LCA with consistent impact indicators. The land rucksack is based on existing methods that are already suitable for practical use and can be maintained and updated through integration with various data sources.

The impact indicators are temporary land occupation and land transformation. They are applied to assign land to a quality category between I and VII based on the degree of human intervention (hemeroby). The two separate impact indicators form the so-called land rucksack and the input variables for the impact category natural land use. The approach thus represents a further development of the method already published in 1999 by the German Environment Agency (Schmitz and Paulini 1999) – updated or revised according to the current state of science and expanded to allow broad application. The case studies demonstrate this broad range of possible applications. They clearly show that land use can be adequately represented in LCA using this approach and that it is compatible with the common methods for evaluation and interpretation.

Like every approach, the land rucksack also has its limitations, and there are still gaps in content that require further research. When considering limitations, it should first be explained that the impacts considered in LCA are always impact potentials. The models and thus also the results for land use are mostly independent of space and time. On the other hand, hemeroby suggests a close link with nature conservation aspects. However, the approach can by no means cover all nature conservation concerns associated with the production or life cycle of a product or service. The impact assessment is limited exclusively to the land effectively occupied or to the change in land use at the production site. Conservation-related impacts that are not solely linked to the land occupation or transformation cannot be taken into account. This includes, for example, the potential risk to birds or bats posed by the rotor movement of a wind turbine.

It is also important to differentiate between the land rucksack and the assessment of biodiversity. As described in Chapter 2.2, there are various approaches for assessing biodiversity in LCA. Strong links exist between hemeroby and biodiversity, and in many cases decreasing hemeroby is accompanied by increasing biodiversity. However, this cannot be generalised. To explore the link, Lindner et al. (2020) have successfully used hemeroby as an indicator of biodiversity and developed a method for assessing biodiversity in life cycle assessments from the criteria and metrics of the approach presented here.

The method is also limited when it comes to assessing land experiencing extreme levels of intervention. In the seven-level classification system, the least favourable classification is class VII, which includes sealed and severely devastated land. A more nuanced assessment and classification may be necessary here. Severely damaged land in particular, where any form of natural development has either permanently ceased or appears impossible in the very long-term, should be assessed with higher hemeroby factors than a sealed land area that can quickly undergo regeneration after unsealing. However, it should again be noted here that ecotoxicological effects are taken into account in the corresponding impact category, e.g. in the case of contamination of waterbodies by toxic wastewater from opencast mining. On the other hand, the quality of other land is also affected by such processes, i.e. as a secondary effect of an activity on the land. Evidently, the boundaries are not quite sharply defined. So far, no methodological concept is available for integrating such severe impacts on the land into the hemeroby scale.

For the reasons outlined above, there is thus a need for further research. The following concerns should be further explored in future projects:

- Extension to the global level: The criteria sets are in principle globally applicable, since the measure of the intensity of human intervention applies independently of geographical factors. However, there is a need to adapt various metrics, which in the current version were developed for Germany and make use of German databases.

- Extension to waterbodies: The present sets were developed exclusively for terrestrial land. However, waterbodies are increasingly affected by human use and should be included in the concept;

this is of particular importance for hydropower, waterways, offshore wind energy, aquaculture as well as fisheries and also submarine resource extraction.

- Land rucksack forest: The criteria have so far only been applied to a few specific cases. Further validation through a series of case studies would be very useful here, for example to refine the approach for the assessment of individual tree species.

- Expansion of the (global) database: With the results of the land rucksack project, a comprehensive number of data sets were created (see Table 5, see page 30), but these are by no means complete and should be further extended with the expansion of the criteria sets to the global level.

The next step would be to link the compiled data to a database system. The ProBas system of the German Environment Agency, which currently lacks consistent land data that could be applied for the land rucksack, could be integrated here.

In addition, comparative studies with alternative approaches, which are now more widely used in LCA, would be particularly interesting and useful. A comparison or even a link with hemeroby classification derived from remote sensing data is also very promising. There are already many links here, for instance in the work of Wellmann et al. (2018).

In sum, the land rucksack as a method for incorporating land use in life cycle assessments with the help of consistent impact indicators is a promising tool that can be applied and integrated in its current form. With the land rucksack, robust statements about the land can be derived from the intensity of human intervention. This avoids the limitation to one or a few variables (e.g. number of animal and plant species on the land area or soil carbon content), instead covering a broad range of factors. With the land rucksack, land use can be mapped with a complexity that is already convincing and will continue to increase with the further development of the method.

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