Int J Life Cycle Assess (2013) 18:1203–1215
DOI 10.1007/s11367-012-0392-0

Principles for life cycle inventories of land use on a global scale

Thomas Koellner · Laura de Baan · Tabea Beck · Miguel Brandao · Barbara Civit · Mark Goedkoop · Manuele Margni · Llorenç Milà i Canals · Ruedi Müller-Wenk · Bo Weidema · Bastian Wittstock

Received: 28 May 2011 / Accepted: 14 February 2012 / Published online: 21 March 2012

Abstract
Purpose To assess the diverse environmental impacts of land use, a standardization of quantifying land use elementary flows is needed in life cycle assessment (LCA). The purpose of this paper is to propose how to standardize the land use classification and how to regionalize land use elementary flows.
Materials and methods In life cycle inventories, land occupation and transformation are elementary flows providing relevant information on the type and location of land use for land use impact assessment. To find a suitable land use classification system for LCA, existing global land cover classification systems and global approaches to define biogeographical regions are reviewed.
Results and discussion A new multi-level classification of land use is presented. It consists of four levels of detail ranging from very general global land cover classes to more refined categories and very specific categories

Responsible editor: Roland Geyer

T. Koellner (✉)
Faculty of Biology, Chemistry and Geosciences,
Professorship of Ecological Services, University of Bayreuth,
GEO II, Room 1.17, Universitaetsstr. 30,
95440 Bayreuth, Germany
e-mail: thomas.koellner@uni-bayreuth.de

L. de Baan
Natural and Social Science Interface,
Institute for Environmental Decisions, ETH Zurich,
Universitaetstr. 22,
8092 Zurich, Switzerland

T. Beck · B. Wittstock
Department Life Cycle Engineering, University of Stuttgart,
Hauptstrasse 113,
70771 Leinfelden-Echterdingen, Germany

M. Brandao
European Commission, Joint Research Centre, Institute for
Environment and Sustainability, Sustainability Assessment Unit,
Via Enrico Fermi 2749,
21027 Ispra, VA, Italy

B. Civit
Facultad Regional Mendoza/CONICET,
Universidad Tecnológica Nacional,
Rodríguez 273,
5500 Mendoza, Argentina

M. Goedkoop
PRé Consultants bv,
Printerweg 18, 3821 BB, Amersfoort, The Netherlands

M. Margni
Département de génie chimique,
CIRAIG, École Polytechnique de Montréal,
6079 Montréal, Canada

L. M. i Canals
Unilever U.K. Central Resources Limited, SEAC, Unilever,
Colworth Park, Sharnbrook,
Bedford MK44 1LQ, UK

R. Müller-Wenk
Institute for Economy and the Environment, University St. Gallen,
Tigerbergstrasse 2,
9000 St. Gallen, Switzerland

B. Weidema
Ecoinvent Centre,
Lerchenfeldstrasse 5,
9014 St. Gallen, Switzerland

indicating land use intensities. Regionalization is built on five levels, first distinguishing between terrestrial, freshwater, and marine biomes and further specifying climatic regions, specific biomes, ecoregions and finally indicating the exact geo-referenced information of land use. Current land use inventories and impact assessment methods do not always match and hinder a comprehensive assessment of land use impact. A standardized definition of land use types and geographic location helps to overcome this gap and provides the opportunity to test the optimal resolution of land cover types and regionalization for each impact pathway.

Conclusions and recommendation The presented approach provides the necessary flexibility to providers of inventories and developers of impact assessment methods. To simplify inventories and impact assessment methods of land use, we need to find archetypical situations across impact pathways, land use types and regions, and aggregate inventory entries and methods accordingly.

Keywords Global · Land cover · Life cycle assessment · Regionalization

1 Introduction

In order to perform an impact assessment of land use within the framework of life cycle assessment (LCA), it is necessary to register the "amount" of land use in life cycle inventories (LCIs). This information on quantity and quality (type, intensity, and location) of land use is needed by several life cycle impact assessment (LCIA) methods to assess land use impacts on biodiversity or ecosystem services, such as, carbon sequestration, biotic production, or erosion regulation (Koellner et al. 2012). To assess the overall impact of land use, the land use elementary flows in the inventory need to be in a format that provides the relevant information to all of these impact assessment methods spatially explicit. The regionalization of land use assessment was identified as one of the major gaps in LCA (Milà i Canals et al. 2007). For the practical development of the LCA methodology, it is crucial to define how to classify land use and how to register the location of land use. In order to allow exchange of data between inventories it would be desirable to standardize the classification and regionalization of land use. The aim of this paper is to present such a possible standardization of land use classification and regionalization to allow a harmonized development of characterization factors (CFs) and inventory databases, which can be used to calculate land use impact sites dependently, according to the scale of the CF.

2 Materials and methods

2.1 Land use elementary flows

In LCA, land occupation and land transformation can be distinguished as basic types of land use elementary flows (Milà i Canals et al. 2007). They result in either damage to or benefits for ecosystem quality. Whereas land transformation causes a change in ecosystem quality, land occupation delays recovery. For example, the conversion of tropical forest into cropland causes a drop in biodiversity and damages the original ecosystem. The continuous use of such cropland hinders the regrowth of tropical forest. In order to assess the impact of such land uses, it is necessary to at least register in the LCI the type of land use, the spatial extent, the temporal extent, and the geographical location (Milà i Canals et al. 2007). In LCIs, the elementary flows of land use are therefore specified as follows:

- For land occupation: square meter × years, land use type i, and region k
- For land transformation: square meter, initial land use type i→final land use type j, and region k

Human activities do not only alter the terrestrial but also the aquatic surface. Some processes imply the occupation or transformation of water surface (e.g., building a street on top of a river) or the bottom of water bodies (e.g., fish trawling). Mila i Canals et al. (2007) define "physical changes in the seabed" as land use-related impacts and distinguish between occupation and transformation impacts. The use of aquatic surface can cause environmental impacts and should be listed in LCIs as this is done in Ecoinvent (Frischknecht and Jungbluth 2007). In the following, we therefore also discuss the classification of surface use on top of or under water bodies. For simplicity, we use the term "land use" to express the use of terrestrial as well as aquatic surface.

2.2 Land use classification for life cycle inventories

In order to perform an analysis of the impact of land use on biodiversity and ecosystem services, it is important to use a comprehensive classification of all existing land uses and resulting land covers, avoiding the tag "unclassified land" while focusing on differentiating land uses only when relevant from an impact assessment point of view. This system has to be applicable at a global scale to allow the comparison of similar products and services coming from different parts of the world.

There is a difference between the terms land cover and land use. Here, we follow Di Gregorio and Jansen (2005) who define land cover as "the observed (bio) physical cover on the earth's surface, including the vegetation (natural or planted) and human constructions (buildings, road, etc.), which cover the earth's surface. Land use is characterized by the arrangements, activities, and inputs people undertake in a certain land cover type to produce, change, or maintain it. Land use establishes a direct link between land cover and the actions of people in their environment."

Land cover classification systems may be a useful instrument for defining types of land transformation and land occupation. At a given location where land use was absent from the near past up to the present time, the actual land cover corresponds to the potential natural vegetation (e.g., grassland, natural). In contrast, land use by humans at present or in the near past generally results in a land cover that is non-natural for this location (e.g., urban land, continuously built). Thus, it is practical to name a type of land occupation after the land cover that is maintained in its previous state by this land occupation: "Occupation as arable land" is a type of land occupation that enforces, against the forces of nature, the continuation of the non-natural land cover "arable land." Further, a conversion of an area's land cover is initiated by a land transformation. A given type of land transformation can therefore be named after a pair of land covers, that is to say, the land cover before transformation and the land cover after transformation. "Transformation from grassland to irrigated arable land" is thus a transformation that converts a preexisting land cover "grassland" towards a new land cover "irrigated arable land."

Below, we discuss available systems for land cover classification, with respect to their appropriateness for naming types of land occupation and land transformation in LCA. A land use classification in LCA should preferentially be derived from a land cover classification system which (1) is widely accepted (so that the chances are good to have access to large and well-maintained data bases), (2) distinguishes land cover types in environmentally relevant classes (also indicating information on land use intensity), and (3) classifies individual cases of land use into types in such a way that they cause roughly similar environmental impacts under given biogeographical conditions (so that reasonable characterization factors can be worked out per land use type and location).

2.3 Existing land use and cover classifications outside LCA

Different projects describe and classify the earth surface (Giri et al. 2005; Latifovic et al. 2004). A common nomenclature including all land cover types found on the earth surface is fundamental in order to homogenize the classification. For this purpose, the Land Cover Classification System (LCCS) software developed by the Food and Agriculture Organization and United Nation Environmental Program (UNEP) was developed (Di Gregorio and Jansen 2005). The LCCS supplies, at the same time, a uniform classification method which still provides flexibility for the description of the land cover in the national and regional levels. These characteristics are relevant in order to compare similar land cover situated in different continents, for example, grassland in Europe compared with grassland in South America. LCCS was used to develop the classification for two important global land cover maps: Global Land Cover 2000 and GlobCover.

The Global Land Cover 2000 (GLC 2000) project developed a new global land cover classification useful for environmental decision support by the industries, governmental, and non-governmental organizations (Bartholomé and Belward 2005). The GLC 2000 classification divides the earth surface into 18 regions. In order to achieve a consistent land cover map, each continent is analyzed individually following the same guidelines. Each region was mapped using the SPOT-4 VEGETATION VEGA2000 sensor. This vegetation sensor of the SPOT-4 satellite provides daily images with global coverage with a pixel resolution of 1 km at the equator.

The GlobCover is a more recent land cover map developed by the European Space Agency (Arino et al. 2007). According to an oral communication with Steffen Fritz (International Institute for Applied Systems Analysis, Austria) it has some advantages compared to GLC 2000: GlobCover has an approximately ten times higher resolution than GLC 2000 (especially in the Amazon, patterns of deforestation can be better seen) and the GlobCover uses fully automated and repeatable classification. However, according to Fritz, a thematic accuracy assessment revealed that for 73% (area weighted) of the land GlobCover showed a similar accuracy than GLC 2000, but in some areas it is clearly less accurate than GLC 2000. At the same time, there is no clear improvement in thematic quality although it has higher data volumes. Some legend classes in GlobCover contain a high number of mosaic classes (e.g., class mosaic cropland/forest or shrub land or grassland), which is a disadvantage for LCA purposes. Another clear disadvantage is the lack of regular and frequent updates of both global land cover maps, which would allow the analysis of changes.

The CORINE Land Cover Project (European Environmental Agency 2000) offers a detailed classification of Europe's land cover. The CORINE program compiles the environmental information to facilitate the decision-making process of the European community's environmental policy. Artificial and natural surfaces are classified by the CORINE system with a spatial resolution of 100 and 250 m which is repeated every 5–10 years. The classification is organized into three levels of detail: on the first level, the main categories are artificial surfaces, agricultural surfaces, forest and semi-natural areas, wetlands, and water bodies. These five categories are divided into 15 classes on the second level and 33 subclasses on the third level. CORINE is a practical classification system for the purpose of LCA because it has a precious advantage; it already describes the urban and industrial infrastructures according to different types of anthropogenic use. For example, the artificial surfaces category distinguishes between rails and roads, airports and railway stations, and built up areas of different levels of intensity. The same is true also for the agricultural areas where the distinct types of cultivation methods are listed. The disadvantage of the CORINE classification is the fact that it only takes the European land cover into account and is therefore limited for a global use.

GLOBIO3 is a new Global Biodiversity Model (Alkemade et al. 2009) in order to assess the impacts of land use changes on terrestrial biodiversity. The land cover classification is based on GLC 2000, aggregating the classes into seven broad land use classes (snow and ice, bare areas, forests, scrublands and grasslands, mosaic: cropland/forest, cultivated and managed areas, and artificial surfaces). For an LCA purpose, this classification can be very coarse for some applications but can help to simplify the GLC 2000 classes.

2.4 Existing land use and cover classifications in LCA

Koellner et al. (Koellner 2003; Koellner and Scholz 2008a; Koellner and Scholz 2008b) elaborates a more detailed CORINE Plus classification that matches the requirements of the LCA better. The proposed CORINE Plus system takes into account the distinct methods applied in cropland and pasture, for example, organic or integrated cultivation. The application of pesticides and the use of organic fertilizers have different impacts on the environment, like monocultures and polycultures can influence the biodiversity or ecosystem services in distinct manners. A disadvantage of the CORINE Plus Classification is its complexity.

The Life Cycle Inventory database ecoinvent 2.0 holds extensive data on land use of industrial processes (Frischknecht and Jungbluth 2007). It uses a land classification, which is based on the CORINE (Plus) Classification, but has a much lower number of land use classes. The disadvantage is that it omits classes, which are near to nature and beneficial from a biodiversity or ecosystem services point of view. For many LCA applications this is not a problem, but for assessing "green" land uses (e.g., occupation of primary forest) to compensate intense land uses (e.g., crop production) the current Ecoinvent classification is not sufficient. Also, the assessment of ecosystem services as input into the production system is not possible without taking near-to nature land uses into account. Ecoinvent database version 3 has based its land classification on the typology presented in this paper (Weidema et al. 2011).

The classification of land use within the LCIA method ReCiPe defines 18 categories. A comparison of land use types as defined in Ecoinvent and ReCiPe can be found in the final report (de Schryver and Goedkoop 2008). For agricultural land use types (crops/weeds, fertile and infertile grassland, tall grassland/herb) a distinction between monoculture, intensive, and extensive land is made. Forests are distinguished by tree types (coniferous, broad-leafed, mixed) and intensity of use (monoculture, plantation, extensive). The advantage of this method is the inclusion of main land use and boundaries (which are of special importance for biodiversity). However, this classification does not necessarily encompass all relevant global land cover types.

2.5 Regionalization of inventories

In order to allow a sophisticated LCIA of land use, a regional approach is required. This is because land use impacts on biodiversity or ecosystem services can be very region specific. For example, the occupation of cropland in a naturally biodiversity poor region in Europe has a different ecological impact compared to the occupation of cropland in a hot spot of biodiversity in Latin America. In the following, we describe some existing approaches to global regionalization.

The Holdridge's life zones system (Holdridge 1947) is characterizing all world regions' vegetation types based on three variables: mean annual precipitation, mean annual biotemperature (the mean of all temperatures above 0°C because below this temperature plants are dormant), and ratio of annual potential evapotranspiration to rainfall. According to these three criteria, it is possible to predict the type of vegetation growing in a certain area. The Holdridge's life zones system is widely used in the scientific literature for the classification of global distribution of vegetation classes.

An alternative is the classification of the terrestrial and freshwater biomes and ecoregions that was developed by Olson et al. (2001). The system of ecoregions is based on a schema of eight biogeographic realms and 14 biomes that are subsequently divided into more than 867 terrestrial and freshwater ecoregions. Each of the ecoregions is described and assessed according to its biodiversity, environmental properties, climatic condition, and habitat diversity. In addition, about 238 ecoregions, both terrestrial and freshwater, with the highest global relevance for biodiversity conservation are defined (Olson and Dinerstein 1998). Freshwater ecosystems are divided in this system into lakes, small rivers and streams, and large rivers. The following marine ecosystems are distinguished: large deltas, mangroves, and estuaries; coral reef and associated marine ecosystems; coastal marine ecosystems; and polar and subpolar marine ecosystems. Spalding et al. (2007) developed a congruent classification for coastal and shelf biomes and ecoregions. The classification is based on information like range discontinuities, dominant habitats, geomorphological features, currents, and temperatures. As a result, the classification does distinguish 12 realms and 232 ecoregions for coastal and shelf ecosystems on a global scale. Those ecoregions are increasingly used for conservation planning by the WWF.

For practical purposes, the political borders of nation countries (n=194) can serve as a basis for regionalization of land use inventories. Inventory data will mostly be more easily available on the level of countries than on ecoregions or biomes. However, for large countries, this scale might be too coarse to reflect the regional differences.

3 Results

3.1 A land use and land cover classification for LCA on a global scale

The development of the classification of land use and land cover as presented in Table 1 is based on the classifications described above. It consists of four levels of detail:

- Level 1 uses very general land use and land cover classes (from GLC 2000),
- Level 2 refines the categories of level 1 (using mainly the classification of ecoinvent v2.0 and GLOBIO3),
- Level 3 gives more information on the land management (e.g., irrigated versus non-irrigated arable land), and
- Level 4 mostly specifies the intensity of the land uses (extensive versus intensive land use). However, for forest and grassland, this information is already given at level 3.

The first level has to fulfill the criterion of global and homogeneous application. This criterion can be satisfied using the GLC 2000 system. The aggregation of the GLC 2000 classes into broader categories allows reducing the complexity. The data from the year 2000 can serve as a baseline to normalize land occupation for all world regions. The other levels of the classification have to take different degrees of land use intensities into account. This criterion can be fulfilled by the classification used in ecoinvent v2.0. However, some changes are introduced:

- First, the class “tropical rain forest” of ecoinvent is deleted because this is a geographical specification, which is done consistently for all land use types with a regionalization approach.
- Second, several new land use types are introduced: occupation with primary forest, coastal wetlands, inland wetlands, grassland, agricultural fallow with hedgerows, urban fallow, and bare areas. This allows assessing such “green” land use types in a LCA framework.
- Third, the classification of areas permanently covered with water is extended (which in ecoinvent v2.0 only consists of the three categories: water courses, artificial; water bodies, artificial; and sea and ocean). We distinguish on the second level between rivers, lakes, and seabed; on the third level, between use, non-use or artificially created; and on the forth level, the use intensity.

The structure into different levels permits to elaborate the analysis according to the level of detail necessary or available. For example, if one decides to compare the environmental impact of occupying a piece of forest, taken as a whole category, with the occupation of grassland, only the first level of classification is needed. On the other hand, the accurate distinctions depicted in the second and third level of the classification system are required if one decides to assess the environmental impacts of different agricultural methods.

A good deal of the N land use classes listed in Table 1 can be expected to appear as types of land occupation in practical life cycle inventories. Theoretically, the corresponding number of possible land transformations is $N\times(N-1)$, but the great majority of these will be of no practical relevance (e.g., transformation from permanent crops to seabed or vice versa).

3.2 Regionalization of land use elementary flows in LCA

The crucial question is what level of geographical detail for land use elementary flows is needed and sensible in LCA studies. The levels of regionalization may well differ between the goals and scope of specific studies. For this purpose, we also suggest a regionalization with different levels of detail. Especially in the foreground system there can be land use elementary flows, which are geo-referenced with exact information on longitude and latitude. For many elementary flows, especially in the background system of LCIs, only coarse geographical information might be available (e.g., on the level of biomes or countries). On the other hand, the required level of regional differentiation may differ for the assessment of individual impact pathways. Further refinement is restricted if the differences between finer spatial differentiation are smaller than the uncertainty in measuring such impacts. For this reason, we propose a flexible system for regionalization of land use on five levels, whereof levels 1, 2, and 3 are explicitly shown in Table 2:

- Level 1: differentiation between terrestrial biomes, freshwater biomes, coastal water, and shelf biomes (shallower than 200 m) and deep sea biomes
- Level 2: climatic regions (tropical/subtropical, temperate, boreal, polar)
- Level 3: classification for terrestrial and freshwater biomes (n=16) by Olson et al. (2001) and classification for marine biomes (n=3) based on the eight realms by Spalding et al. (2007). The biomes can be further distinguished for continental plates: Australasia, Afrotropic,

Table 1 Land use and cover classification for LCA

ID_use	Land use/cover class	Description mainly taken from Alkemade et al. 2009; Koellner and Scholz 2008a, and ecoinvent 3.0
0	Unspecified	Land use and cover not known
0.1	Unspecified, used	Human land use and resulting land cover not known
0.2	Unspecified, natural (*)	Natural land cover not known
1.	Forest[a]	Areas with tree cover >15%
1.1	Forest, natural (*)	Forest not used by humans
1.1.1	Forest, primary	Forests minimally disturbed by human impact, where flora and fauna species abundance is near pristine
1.1.2	Forest, secondary	Areas originally covered with forest or woodlands, where vegetation has been removed, forest is re-growing and is no longer in use
1.2	Forest, used	Forests used by humans
1.2.1	Forest, extensive	Forests with extractive use and associated disturbance like hunting, and selective logging, where timber extraction is followed by re-growth including at least three naturally occurring tree species
1.2.2	Forest, intensive	Forests with extractive use, with either even-aged stands and clear-cut patches, or less than three naturally occurring species at planting/seeding
2.	Wetlands	Areas regularly flooded, eventually with tree cover, closed to open (>15%)
2.1	Wetlands, coastal[b] (*)	Areas tidally, seasonally or permanently waterlogged with brackish or saline water. Includes costal marshland, mangroves and salt marshes. Excludes coastal land with infrastructure or agriculture
2.2	Wetlands, inland[c] (*)	Areas partially, seasonally, or permanently waterlogged. The water may be stagnant or circulating. Includes inland marshland, swamp forests and peat bogs
3.	Shrub land[d] (*)	Areas with shrub-dominated sclerophyllous vegetation
4.	Grassland[e]	Herbaceous cover, closed to open (>15%) with scattered shrubs or trees
4.1	Grassland	Naturally grassland dominated vegetation
4.1.1	Grassland, natural (*)	Grassland-dominated vegetation, fauna and flora near pristine (e.g., steppe, tundra, savannah)
4.1.2	Grassland, for livestock grazing	Grasslands where wildlife is replaced by grazing livestock
4.2	Pasture/meadow	Areas that have been converted to grasslands for livestock grazing or fodder production
4.2.1	Pasture/meadow, extensive	Pasture with low number of livestock or meadows mechanically harvested 2 or 3 times per year, reduced input of fertilizer
4.2.2	Pasture/meadow, intensive	Pasture with high number of livestock or meadows mechanically harvested 3 times or more per year, fertilizer applied
5.	Agriculture[f]	Areas used for crop production
5.1	Arable	Cultivated areas regularly ploughed and generally under a rotation system. Cereals, legumes, fodder crops, and root crops. Includes flower and tree (nurseries) cultivation and vegetables as well as aromatic, medicinal and culinary plants. Excludes permanent pastures
5.1.1	Arable, fallow	Cropland temporarily not used (<2 years)
5.1.2	Arable, non-irrigated	Annual crop production based on natural precipitation (rainfed agriculture)
5.1.2.1	Arable, non-irrigated, extensive	+ Use of chemical–synthetic and organic fertilizer as well as pesticides is reduced
5.1.2.2	Arable, non-irrigated, intensive	+ Chemical–synthetic and organic fertilizer as well as pesticides are applied
5.1.3	Arable, irrigated	Annual crops irrigated permanently or periodically, using a permanent infrastructure (irrigation channels, drainage network). Most of these crops like rice could not be cultivated without an artificial water supply. Does not include sporadically irrigated land
5.1.3.1	Arable, irrigated, extensive	+ Use of chemical–synthetic and organic fertilizer as well as pesticides is reduced
5.1.3.2	Arable, irrigated, intensive	+ Chemical–synthetic and organic fertilizer as well as pesticides are applied
5.1.4	Arable, flooded crops	

Table 1 (continued)

ID_use	Land use/cover class	Description mainly taken from Alkemade et al. 2009; Koellner and Scholz 2008a, and ecoinvent 3.0
		Areas developed for rice cultivation. Flat surfaces with irrigation channels. Surfaces regularly flooded
5.1.5	Arable, greenhouse	Crop production under plastic or glass
5.1.6	Field margins/hedgerows	Areas between fields with natural vegetation
5.2	Permanent crops	Perennial crops not under a rotation system which provide repeated harvests and occupy the land for a long period before it is ploughed and replanted: mainly plantations of woody crops
5.2.1	Permanent crops, non-irrigated	Perennial crops production based on natural precipitation (rainfed agriculture)
5.2.1.1	Permanent crops, non-irrigated, extensive	+ Use of chemical–synthetic and organic fertilizer as well as pesticides is reduced
5.2.1.2	Permanent crops, non-irrigated, intensive	+ Chemical–synthetic and organic fertilizer as well as pesticides are applied
5.2.2	Permanent crops, irrigated	Perennial crops with artificial input of water
5.2.2.1	Permanent crops, irrigated, extensive	+ Use of chemical–synthetic and organic fertilizer as well as pesticides is reduced
5.2.2.2	Permanent crops, irrigated, intensive	+ Chemical-synthetic and organic fertilizer as well as pesticides are applied
6.	Agriculture, mosaic[g]	Heterogeneous, agricultural production intercropped with (native) trees. Trees or shrubs are kept for shade or as wind shelter; or use of timber or non-timber products (e.g., agroforestry)
7.	Artificial areas[h]	Artificial surfaces and associated area(s)
7.1	Urban	Areas with infrastructure for living and businesses
7.1.1	Urban/industrial fallow	Areas with remains of industrial buildings; deposits of rubble, gravel, sand and industrial waste. Can be vegetated
7.1.2	Urban, continuously built	Buildings cover most of the land. Roads and artificially surfaced area cover almost all the ground. Non-linear areas of vegetation and bare soil are exceptional. At least 80% of the total area is sealed
7.1.3	Urban, discontinuously built	Most of the land is covered by structures. Buildings, roads, and artificially surfaced areas associated with areas with vegetation and bare soil, which occupy discontinuous but significant surfaces. Less than 80% of the total area is sealed
7.1.4	Urban, green areas	Areas with vegetation within urban fabric. Includes parks with vegetation
7.2	Industrial area	Artificially surfaced areas (with concrete, asphalt, or stabilized, e.g., beaten earth) devoid of vegetation occupy most of the area in question, which also contains buildings and/or areas with vegetation
7.3	Mineral extraction site	Areas with open-pit extraction of industrial minerals (sandpits, quarries) or other minerals (opencast mines). Includes flooded gravel pits, except for riverbed extraction
7.4	Dump site	Landfill or mine dump sites, industrial or public
7.5	Construction site	Areas under construction development, soil or bedrock excavations, earthworks
7.6	Traffic area	Areas used for traffic infrastructure
7.6.1	Traffic area, road network	Motorways, including associated installations (gas stations)
7.6.2	Traffic area, rail network	Railways, including associated installations (stations, platforms)
7.6.3	Traffic area, rail/road embankment	Vegetated area along motorways and railways
8.	Bare area[i] (*)	Areas permanently without vegetation (e.g., deserts, high alpine areas)
9.	Snow and ice[j] (*)	Areas permanently covered with snow or ice considered undisturbed
10.	Water bodies[k]	Areas covered permanently with water
10.1	Rivers	Areas covered with watercourses
10.1.1.	Rivers, natural (*)	Rivers nearly undisturbed by human use
10.1.2	Rivers, artificial	Artificial watercourses serving as water drainage channels. Includes canals

Table 1 (continued)

ID_use	Land use/cover class	Description mainly taken from Alkemade et al. 2009; Koellner and Scholz 2008a, and ecoinvent 3.0
10.1.3	Rivers, used	Riverbed heavily influenced by human use, e.g. due to straightening or infrastructure.
10.2	Lakes	Body of slow-moving or standing water that occupies an inland basin
10.2.1	Lakes, natural (*)	Lakebed, nearly undisturbed by human use
10.2.2	Lakes, artificial	Reservoir in a valley because of damming up a river
10.2.3	Lakes, used	Lakebed disturbed by human use, e.g., by infrastructure
10.3	Seabed	Areas covered permanently with salt water
10.3.1	Seabed, natural (*)	Natural seabed, nearly undisturbed by human use
10.3.2	Seabed, used	Seabed influenced by human use
10.3.2.1	Seabed, fisheries for dredging	Seabed disturbed by dredging due to fisheries
10.3.2.2	Seabed, sediment dumping	Seabed disturbed due to dumping of sediments
10.3.2.3	Seabed, marine infrastructure	Seabed disturbed due to infrastructure like harbors or platforms
10.3.2.4	Seabed, oil drilling	Sea bed disturbed due to oil drilling
10.3.2.5	Seabed, mining	Sea bed disturbed due to mining

Level 1 is based on GLC 2000 and the other levels mainly on ecoinvent v2.0 and GLOBIO3. The (*) marks land cover types, which serve as a natural reference

Classification according to GLC 2000 (Bartholomé and Belward 2005)

[a] 1. Tree cover, broad-leaved evergreen, closed to open (>15%) and 2. Tree Cover, broad-leaved deciduous, closed (>40%) and 3. Tree cover, broad-leaved deciduous, open (15–40%) and 4. Tree cover, needle-leaved evergreen, closed to open (>15%) and 5. Tree cover, needle-leaved deciduous, closed to open (>15%) and 6. Tree cover, mixed leaf type, closed to open (>15%) and 9. Mosaic of tree cover and other natural vegetation and 10. Tree cover, burnt (mainly boreal forests)

[b] 7. Tree cover, closed to open (>15%), regularly flooded, saline water: mangrove forests

[c] 8. Tree cover, closed to open (>15%), regularly flooded, fresh or brackish water: swamp forests and 15. Regularly flooded (>2 months) shrub and/or herbaceous cover

[d] 11. Shrub cover closed to open (>15%), evergreen (broad-leaved or needle-leaved) and 12. Shrub cover closed to open (>15%), deciduous (broad-leaved) and 14. Sparse herbaceous or sparse shrub cover

[e] 13. Herbaceous cover, closed to open (>15%)

[f] 16. Cropland (upland crops or inundated/ flooded crops as, e.g., rice)

[g] 17. Mosaic of cropland/tree cover/other natural vegetation and 18. Mosaic of cropland/shrub or herbaceous cover

[h] 22. Artificial surfaces and associated area(s)

[i] 19. Bare areas

[j] 21. Snow and ice

[k] 20. Water bodies

[+] Perennial crops production based on natural precipitation (rainfed agriculture) with use of chemical–synthetic and organic fertilizer as well as pesticides is reduced

Indo-Malayan, Nearctic, Neotropic, Oceania, and Palearctic

- Level 4: Olson terrestrial and freshwater ecoregions (n=867 and n=238 priority regions) and Spalding coastal and shelf ecoregions (n=232) as shown in Fig. 1; no differentiation for deep sea
- Level 5: exact geo-referenced information of land use in grid cells of 1.23 km^2 or less defined by degrees longitude and latitude with two decimals, which allows to derive elevation of land use (above and below sea level)

It is important to note that higher-level geographical information can unambiguously be transformed into lower-level information (e.g., the ecoregions can be consistently transformed into biomes in the system developed by Olson). This might be necessary in order to perform an impact assessment, which does not require detailed spatial information (for example, for CFs for the carbon sequestration potential, Müller-Wenk and Brandão 2010).

3.3 Generic characterization factors to assess the impact of land use elementary flows

For each impact pathway, CFs can be displayed at the required or available level of detail both for the geographic location and the land use type. In Table 3, which is a combination of Table 1 and Table 2, this combination is illustrated for land occupation impacts. The vertical axis

Table 2 Terrestrial, freshwater, and costal water and marine biomes for regionalization of land use inventories (or surface use for freshwater and marine biomes)

ID_region	Name of biomes	ID biomes
1.	Terrestrial biomes	
1.1	Tropical and subtropical terrestrial biomes	
1.1.1	Tropical and subtropical moist broadleaf forests	B01
1.1.2	Tropical and subtropical dry broadleaf forests	B02
1.1.3	Tropical and subtropical coniferous forests	B03
1.1.4	Tropical and subtropical grasslands, savannas and shrublands	B07
1.1.5	Flooded grasslands and savannas	B09
1.1.6	Mangroves	B14
1.1.7	Deserts and xeric shrublands	B13
1.2	Temperate terrestrial biomes	
1.2.1	Temperate broadleaf and mixed forests	B04
1.2.2	Temperate coniferous forests	B05
1.2.3	Temperate grasslands, savannas, and shrublands	B08
1.2.4	Mediterranean forests, woodlands, and scrub	B12
1.2.5	Deserts and xeric shrublands	B13
1.3	Boreal terrestrial biomes	
1.3.1	Boreal forests/taiga	B06
1.3.2	Tundra	B11
1.3.3	Montane grasslands and shrublands	B10
1.3.4	Deserts and xeric shrublands	B13
1.4	Polar terrestrial biomes	
1.4.1	Rock and ice	
1.4.2	Deserts and xeric shrublands	
2.	Freshwater biomes	
2.1	Tropical and subtropical freshwater biomes	
2.2	Temperate freshwater biomes	
2.3	Boreal freshwater biomes	
2.4	Polar freshwater biomes	
3.	Coastal water and shelf biomes (shallower than 200 m)	
3.1	Tropical coastal and shelf biomes[a]	
3.2	Temperate coastal and shelf biomes[b]	
3.3	Polar coastal and shelf biomes[c]	
4.	Deep sea biomes (deeper than 200 m)	

Classification according to Marine realms as shown in Fig. 2 from Spalding et al. (2007)

[a]Eastern Indo-Pacific, tropical eastern Pacific, tropical Atlantic, western Indo-Pacific, central Indo-Pacific

[b]Temperate Northern Pacific, temperate Northern Atlantic, temperate Northern Pacific, temperate South America, temperate Southern Africa, temperate Australasia

[c]Arctic, southern ocean

contains the land use types, and the horizontal axis contains the geographical location where the land use takes place. The cells of Table 3 contain the CFs for a given type of land occupation inside a given geographical perimeter. If impacts are assessed on *M* different impact pathways originating from land use, there will be *M* different versions of Table 3, each of them containing the CFs for one impact pathway. However, most of the cells of a Table 3 will be empty because the corresponding pair of land use/location does not exist or is irrelevant for usual LCA practice.

For land transformation, in every geographic location, each of the land use types in the vertical axis can theoretically be transformed into all other land use types. In practice, only a small selection of these combinations is relevant within a specific geographic location (e.g., the land use elementary flow "transformation from primary forest" makes little sense in the geographic location "deserts & xeric shrublands").

Those who compile LCIs have the choice to indicate the type of land use, as well as its geographical location, at any of the differentiation levels proposed in the preceding sections, depending on the information available to them. On the other hand, developers of CFs must have the choice to calculate the CFs at the differentiation level which is adequate with respect to the available knowledge on impact mechanisms and on empirical data. This means that an LCA software has to solve the problem of retrieving the suitable CFs, starting from a given land use entry in the LCI. This matching problem is particularly complicated in the case of land use because each land use entry in LCI needs to be

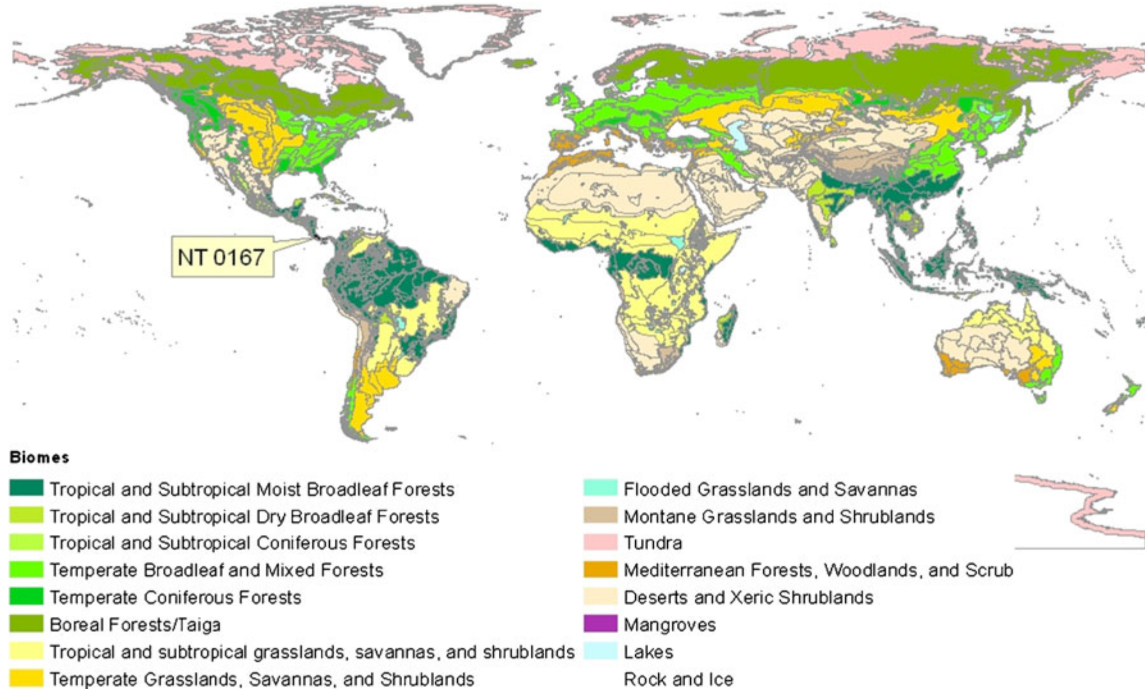

Fig. 1 Terrestrial and freshwater biomes and ecoregions according to Olson et al (2001). The *arrow* shows the location of the Ecoregion NT0167 (Talamancan montane forests in Costa Rica)

connected with CFs of several impact pathways, which provide CFs for a set of land classification and regionalization on different levels of details.

For each of the impact pathways, the respective Table 3 contains CFs in cells defined by the selected level of geographical differentiation and the selected level of land use types. For example, if the supplier of CFs for carbon sequestration potential (CSP) decides to work out CFs for the geographical perimeter of eight biomes (i.e., deserts, tundra, boreal forests, temperate grasslands, temperate forests, tropical grasslands, tropical dry forests, tropical wet forests), and inside each biome for a few important level 1 types of land occupation and types of land transformation, the corresponding Table 3 will contain less than 100 CF entries.

If a given LCI entry (e.g., occupation of 300,000 m^2 of arable land during 1 year inside biome boreal forests) calls for the suitable CF with respect to pathway CSP, the retrieving algorithm tries to find the appropriate CF stored in Table 3 cell determined by row "5.1 arable" and column "1.3.1 boreal forests." The following cases are possible:

- The search finds the CF at the same levels of geographical differentiation and of type differentiation (in our example a CF for "occupation, arable" in the field defined by row "5.1 arable" and column "1.3.1 boreal forests." Then the 300,000 $m^2 \times$yrs can simply be multiplied with the retrieved CF, to obtain the amount of the impact.
- The search finds a CF only at a less differentiated level $n-1$ for type and/or geographical differentiation (in our example, a CF for "occupation, arable" in the field defined by row "5.1 arable" and column "1.3 boreal terrestrial biomes"). Then the 300,000 m^2 can again simply be multiplied with the retrieved unique CF. However, the assessment will be coarser than in the preceding case.
- The search finds CFs only at a more differentiated level $n+1$ for type and/or geographical differentiation (in our example, the search is directed to the fields defined by column "1.3.1 boreal forests" and rows "5.1.2 arable/nonirrigated," "5.1.3 arable/irrigated," "5.1.4 arable/flooded," "5.1.5 arable/greenhouse" because these rows are all linked to "5.1 arable." In this case, there is no unique relationship from the LCI entry to one field, and the CFs of the fields at level $n+1$ for the land use type are equally eligible. It is proposed here that in this situation, the "worst case principle" is applied, i.e., the program selects the CF for "occupation, arable" with the highest (damaging) impact magnitude and multiplies the 300,000 $m^2 \times$yrs with this worst CF.
- In certain cases, the search may find a CF, which shows a value of zero. This means that the impact of the given LCI entry with respect to the CSP pathway is considered to be negligible. The multiplication of the 300,000 $m^2 \times$ yrs with this CF will then yield a zero impact.
- The search finds no matching CF at any level of differentiation, be it equal or higher or lower than the level of differentiation of the LCI entry. In this case, the impact

Table 3 Exemplary cross tabulation with land use types (Forest) and biomes (Terrestrial) for organizing generic characterization factors CFs for land occupation

Land use types	Regions	1. Terrestrial biomes	1.1 Tropical and subtropical terrestrial biomes	1.1.1 Tropical and subtropical moist broad-leaf forests	1.1.1.1 Talamancan montane forests (NT0167)
0. Unspecified		a			
1. Forest			b		
1.1 Forest, natural					
1.1.1 Forest, primary				e→	d
1.1.2 Forest, secondary					
1.2 Forest used					
1.2.1 Forest, extensive					
1.2.2 Forest, intensive				c; →e	

For the full classification of land use types please refer to Table 1 and for the full regionalization to Table 2. The horizontal lines (–) indicate where CFs are not applicable. The complete table as an Excel file can be found at the homepage of the LULCIA project at http://www.pes.uni-bayreuth.de/en/research/projects/LULCIA. In general, each cell holds a CF for a specific land use in a specific region, it is $CF^{Region}_{Landuse}$, e.g., (a) holds the $CF^{R1.}_{L0.}$ for unspecified land occupation in an unknown location on land, (b) holds the $CF^{R1.1}_{L1.}$ for land occupation with unspecified forests in tropical and subtropical biomes, (c) holds the $CF^{R1.1.1}_{L1.2.2}$ for land occupation with intensively used forests in the biome of tropical and subtropical moist broadleaf forests (see Fig. 1 for the geographical extent of this biome), (d) $CF^{R1.1.1.NT0167}_{L1.2.2}$ holds the CF for the same land use in the ecoregion NT0167 (Talamancan montane forests). Based on this system, CF for land transformation can be build accordingly, e.g., (e) $CF^{R1.1.1}_{L1.1.1\rightarrow L1.2.2}$ gives the CF for land transformation from primary forest to intensively used forests in the biome of tropical and subtropical moist broadleaf forests by splitting the CF into transformation from (e→) and transformation to (→e)

assessment is not feasible, and the inventory entry needs to be flagged to express this fact.

This matching algorithm gives the necessary freedom of choice to the producers of LCIs, as well as to the developers of CF sets for particular impact pathways, so that they have a better chance of obtaining results that are applicable in LCA practice.

4 Discussion

The environmental relevance of land use impacts of processes such as mining or agricultural production is reflected in the increasing availability of LCIA methods of different impact pathways, such as, biodiversity, carbon sequestration, or erosion regulation. These methods rely on inventories providing relevant information on quantity, quality, and location of land use elementary flows. Both the inventories and the impact assessment methods have requirements and constraints in the levels of detail they can provide, which calls for a standardized approach for land use classification and regionalization that helps to overcome such barriers. In the approach presented above, the provider of inventory data has the possibility to indicate the level of detail available—from very coarse distinction between land, freshwater or marine surface use, to the exact geographic location—and the developer of an impact assessment method can choose the appropriate and feasible level of detail to calculate CFs of a specific impact pathway. On both sides, missing availability of data or information might reduce accuracy. To allow an assessment of land use, we propose an algorithm to be included in LCA software to match land use elementary flows with the available CFs of different impact pathways. The hierarchical approach allows also testing the suitability of the proposed classification system for different impact pathways.

For some impact pathways, such as, erosion potential, the presented regionalization approach might not be ideal. The biome and ecoregion concept delineate biologically similar areas, but for erosion the indication of the catchment and slope of a land use type might be more relevant. Here, the regionalization of freshwater ecoregions, as proposed by Abell et al. (2008) might be a useful alternative because it considers water catchments to delineate regions. Thus, these freshwater ecoregions classify the entire continental surface according to hydrological drainage basins and according to characteristics of freshwater ecosystems, such as, distributions and compositions of freshwater fish species and major ecological and evolutionary patterns while the freshwater ecoregions defined by Olson et al. (2001) only classify the water bodies. However, there is no direct connection between Abell's freshwater ecoregions and Olson's terrestrial, and the two concepts cannot be linked in an unambiguous way (e.g., the terrestrial ecoregion Talamancan montane forests (NT0167) forms a water barrier and includes several freshwater ecoregions). Therefore, the use of two different concepts for regionalization for different impact pathways would be needed.

The proposed land use classification shows different levels of detail for different sectors. Agricultural land is specified up to level 4 (e.g., "5.1.3.2 Arable, irrigated, intensive"), whereas for other sector land use, the differentiated stops at level 2 (e.g. “7.3 Mineral extraction site”). For specific assessments of land use impacts, further refinement might be necessary in future. With the hierarchical structure of the land use classification, this can be done more easily.

The aim of this paper was to propose how to standardize the land use classification and how to regionalize land use elementary flows. For some applications, for example, the comparison of different locations for agricultural purposes, more precise, site-specific considerations might be of interest. As site-specific conditions of, e.g., soil parameters, do vary considerably within one land use class even regarding small plots, the approach of using site-dependent CFs is not applicable in such cases. In these cases, an alternative approach might be favorable. The Land Use Indicator Calculation Tool LANCA (Beck et al. 2010) calculates site-specific indicator values and determines the CFs based on site-specific input data that has to be entered into the tool. These indicator values, already including inventory and impact assessment information, can then be included into current LCA tools as “indicator value flows”. So, whereas the use of site-dependent CFs leaves some degrees of freedom to the user inside the LCA tool (provision of area, time and type of land use), a LANCA user has the freedom to define all parameters influencing the indicator value calculations according to his requirements, but once the results are included into the LCA software, there is no more scope of influence for the user.

5 Conclusions and recommendations

To date, no standardized classification and regionalization of land use inventories and impact assessment methods exist. This hinders a holistic assessment of land use-related impacts on biodiversity and ecosystem services, such as, biotic production, carbon sequestration, fresh water regulation, erosion regulation, and water purification. The hierarchical approach presented in this paper provides the possibility to test hypothesis about optimal land classifications and regionalization. It has also the necessary flexibility to providers of inventories and developers of impact assessment methods and overcomes the problems of mismatching definitions between both. However, the presented approach creates immense work and data requirements to provide CFs for all practically relevant combinations of land use types and regions. Comparing the median and percentiles of the distributions of characterization factors across land cover types and regions would allow to test whether CFs are significantly different. The developers of CFs should aim at finding archetypical situations for their specific impact pathways, which would allow aggregating CFs of land use types or locations and reduce the amount of CFs to be provided. Such analysis could also reveal if the environmental variability within ecoregions is rather high and that a finer regionalization would improve the reliability of the CFs. Unfortunately, a meaningful simplification can only be achieved, when the detailed information of land use impacts across land use types, regions, and impact pathways will be available.

Acknowledgments The authors wish to thank the UNEP/SETAC Life Cycle Initiative for the financial support of this work under the project Operational Characterization Factors for Land Use Impacts on Biodiversity and Ecosystem Services in the Life-Cycle Impact Assessment (LULCIA). The research was partly funded by the European Commission under the seventh framework program on environment; ENV.2009.3.3.2.1: LCIMPACT–Improved Life Cycle Impact Assessment methods (LCIA) for better sustainability assessment of technologies, grant agreement number 243827.

References

Abell R, Thieme M, Revenga C, Bryer M, Kottelat M, Bogutskaya N, Coad B, Mandrak N, Balderas S, Bussing W (2008) Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation. BioScience 58:403–414

Alkemade R, van Oorschot M, Miles L, Nellemann C, Bakkenes M, ten Brink B (2009) GLOBIO3: a framework to investigate options for reducing global terrestrial biodiversity loss. Ecosystems 12:374–390

Arino O, Gross D, Ranera F, Leroy M, Bicheron P, Brockman C, Defourny P, Vancutsem C, Achard F, Durieux L, Bourg L, Latham J, Gregorio AD, Witt R, Herold M, Sambale J, Plummer S, Weber J (2007) GlobCover: ESA service for global land cover from MERIS. Geoscience and Remote Sensing Symposium, 2412-2415

Bartholomé E, Belward AS (2005) GLC2000: a new approach to global land cover mapping from Earth observation data. Int J Remote Sens 26:1959–1977

Beck T, Bos U, Wittstock B, Baitz M, Fischer M, Sedlbauer K (2010) LANCA—land use indicator value calculation in life cycle assessment. Fraunhofer, Stuttgart

de Schryver A, Goedkoop M (2008) Impact of land use in M. Goedkoop , R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, R. van Zelm, eds. ReCiPe. A life cycle impact assessment method which comprises harmonised category indicatorsat the midpoint and the endpoint level, Online at http://www.lcia-recipe.net/@api/deki/files/11/=ReCiPe_main_report_final_27-02-2009_web.pdf

Di Gregorio A, Jansen LJM (2005) Land Cover Classification System (LCCS) classification concepts and user manual. Environment and Natural Resources Service (SDRN), Food and Agricultura Organisation of the United Nations, Rome

European Environmental Agency (2000) CORINE Land Cover. European Environmental Agency, Luxembourg

Frischknecht R, Jungbluth N (eds) (2007) Ecoinvent: overview and methodology. Swiss Centre for Life Cycle Inventories, Duebendorf

Giri C, Zhu Z, Reed B (2005) A comparative análisis of the Global Land Cover 2000 and MODIS land cover data sets. Remote Sens Environ 94:123–132

Holdridge LR (1947) Determination of world plant formations from simple climatic data. Science 105:367–368

Koellner T (2003) Land use in product life cycles and ecosystem quality. Peter Lang, Bern, Frankfurt a. M., New York

Koellner T, Scholz R (2008a) Assessment of land use impacts on the natural environment. Part 2: Generic characterization factors for local species diversity in Central Europe. Int J Life Cycle Assess 13:32–48

Koellner T, Scholz RW (2008b) Assessment of land use impacts on the natural environment. Appendix: CORINE Plus land-cover definitions. Int J Life Cycle Assess 13:48-1–48-3

Koellner T, de Baan L, Beck T, Brandão M, Civit B, Margni M, Milà i Canals L, Saad R, Maia de Souza D, Müller-Wenk R (2012) UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA. Int J Life Cycle Assess (this issue)

Latifovic R, Zhu ZL, Cihlar J, Giri C, Olthof I (2004) Land cover mapping of North and Central America—global land cover 2000. Remote Sens Environ 89:116–127

Milà i Canals L, Bauer C, Depestele J, Dubreuil A, Freiermuth Knuchel R, Gaillard G, Michelsen O, Müller-Wenk R, Rydgren B (2007) Key elements in a framework for land use impact assessment within LCA. Int J Life Cycle Assess 12. doi:5

Müller-Wenk R, Brandão M (2010) Climatic impact of land use in LCA—carbon transfers between vegetation/soil and air. Int J Life Cycle Assess 15:172–182

Olson DM, Dinerstein E (1998) The global 200: a representation approach to conserving the Earth's most biologically valuable ecoregions. Conserv Biol 12:502–515

Olson DM, Dinerstein E, Wikramanayake ED, Burgess ND, Powell GVN, Underwood EC, D'Amico JA, Itoua I, Strand HE, Morrison JC, Loucks CJ, Allnutt TF, Ricketts TH, Kura Y, Lamoreux JF, Wettengel WW, Hedao P, Kassem KR (2001) Terrestrial ecoregions of the worlds: a new map of life on Earth. BioScience 51:933–938

Spalding MD, Fox HE, Halpern BS, McManus MA, Molnar J, Allen GR, Davidson N, Jorge ZA, Lombana AL, Lourie SA, Martin KD, McManus E, Molnar J, Recchia CA, Robertson J (2007) Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. Bioscience 57:573–583

Weidema B, Bauer C, Hischier R, Mutel C, Nemecek T, Vadenbo CO, Wernet G (2011) Overview and methodology. Data quality guideline for the ecoinvent database version 3. Ecoinvent Report 1(v3). The ecoinvent Centre, St. Gallen