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Exergy-based accounting for land as a natural resource in life cycle assessment

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Abstract

Purpose In life cycle assessment (LCA), literature suggests accounting for land as a resource either by what it delivers (e.g., biomass content) or the time and space needed to produce biomass (land occupation), in order to avoid double-counting. This paper proposes and implements a new framework to calculate exergy-based spatial explicit characterization factors (CF) for land as a resource, which deals with both biomass and area occupied on the global scale.

Methods We created a schematic overview of the Earth, dividing it into two systems (human-made and natural), making it possible to account for what is actually extracted from nature, i.e., the biomass content was set as the elementary flow to be accounted at natural systems and the land occupation (through the potential natural net primary production) was set as the elementary flow at human-made systems. Through exergy, we were able to create CF for land resources for these two different systems. The relevancy of the new CF was tested for a number of biobased products.

Results and discussion Site-generic CF were created for land as a resource for natural systems providing goods to humans, and site-generic and site-dependent CF (at grid, region, country, and continent level) were created for land as a resource within human-made systems. This framework differed from other methods in the sense of accounting for both land occupation and biomass content but without double-counting. It is set operationally for LCA and able to account for land resources with more completeness, allowing spatial differentiation. When site-dependent CF were considered for land resources, the overall resource consumption of certain products increased up to 77 % in comparison with site-generic CF-based data.

Conclusions This paper clearly distinguished the origin of the resource (natural or human-made systems), allowing consistent accounting for land as a resource. Site-dependent CF for human-made systems allowed spatial differentiation, which was not considered in other resource accounting life cycle impact assessment methods.

Keywords Biomass · Exergy · Land · LCA · NPP · Resource

1 Introduction

With the World's population projected to grow from 6.9 billion in 2010 to more than 9 billion in 2050 (United Nations 2009) associated with a growth rate of 5 % of the Human Development Index from 1980 to 2010 (United Nations 2010), the consumption of overall Earth resources is expected to rise. Due to the depletion of non-renewable resources and policy actions to mitigate climate change, an increase pressure on land as a resource is to be expected (Bessou et al. 2011; Easterling and Apps 2005). Land use addresses several environmental impacts and can affect the ecosystem services (MEA 2005). Much effort is being done

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by the scientific community in order to consider these consequences on the environment when using life cycle assessment (LCA) methodology (de Baan et al. 2012; Mila i Canals et al. 2007; Wagendorp et al. 2006; Zhang et al. 2010a, b). With respect to the provisioning services (one category of ecosystem services), humans harvest the natural resources, e.g., wood and metals, or they fully occupy the land for productive or non-productive uses, e.g., agriculture and urbanization, respectively.

When accounting for the cumulative resource consumption of a certain product through LCA, provisioning services from land, which hereafter will be called as *land resources*, can be quantified through several approaches that may be divided in two groups (Liao et al. 2012). The first group of approaches considers the Earth as a closed system and includes the ecological processes that induce the resource production, with solar, geothermal, and tidal energies as major energy inputs. In this group, the *cradle* (International Organization for Standardization (ISO) 2006) may be defined as the Sun. Emergy analysis (Odum 1996), the ecological cumulative exergy analysis (Hau and Bakshi 2004), and the solar energy demand (Rugani et al. 2011) are examples of approaches from this first group. The second group considers only what is delivered by nature to humans, i.e., they limit their system boundaries to the border between ecosphere and technosphere. In other words, the *cradle* is the natural environment. This last group of approaches is often used in LCA as life cycle impact assessment (LCIA) method and is usually considered as a midpoint indicator in the impact pathway of resource depletion (Liao et al. 2012; European Commission 2011). Regarding land resources, there are basically two ways for accounting: (a) by the content of the biomass harvested, e.g., cumulative energy demand (CED) (Hischier et al. 2009) and cumulative exergy demand (CExD) (Boesch et al. 2007); and (b) by the area and time needed to produce the biomass (land occupation), e.g., cumulative exergy extraction from the natural environment (CEENE) (Dewulf et al. 2007). These methods account for the overall cumulative resource consumption of a product during its life cycle (fossils, water, metals, land, etc.). Specifically for land resources, they needed to choose one way of accounting in order to avoid double-counting, i.e., to keep away from accounting land resources twice. It is also common that some other LCIA methods use the occupation of areas (which is expressed by a *land occupation* elementary flow) to assess impacts on biodiversity on an endpoint level (Bare et al. 2000; Finnveden et al. 2009), and results on midpoint level are provided as well (Goedkoop et al. 2009; Guinée et al. 2002; Jolliet et al. 2003). In these cases, land occupation is accounted, but it is not explicitly considered as a natural resource. Furthermore, even though it is known that the environmental impacts of a product, along its life cycle, may happen at many different locations of the world, most of the LCIA methods neglect this spatial variation. This differentiation is relevant for all non-global impact categories, including land resources (Finnveden et al. 2009; Hauschild 2006).

This paper proposes and implements a new framework to calculate exergy-based spatial explicit characterization factors (CF) for land resources in LCA, limiting the cradle to the border between ecosphere and technosphere, and dealing both with biomass and area occupation on the global scale. Exergy is used as indicator due to its scientific concept that comes from the Second Law of Thermodynamics, which is ruling ecosystems and which reflects the physical and chemical potential and usefulness of resources (Dewulf et al. 2008) and due to its completeness for resource use accounting (Liao et al. 2012). Also, because other natural resources (e.g., fossil fuels) can be expressed in the same unit, it provides a straightforward resource accounting method and allows all resources to be aggregated into a single score (Dewulf et al. 2007; Boesch et al. 2007). Exergy has several uses in environmental science and technology (Dewulf et al. 2008), but it is important to make clear that the use of exergy in this paper is focused on the cumulative resource accounting perspective (and specific for land resources). The CF calculated in this paper ought to be integrated into overall resource exergy-based methods, as the CExD and the CEENE. The relevancy of the new CF is tested for a number of biobased products.

2 Materials and methods

2.1 Framework

For the approaches that set the cradle to the natural environment, it is important to make a clear definition of where the frontier between ecosphere and technosphere is located, through naturalness levels. The most straightforward way is to divide in two levels: natural and human-made systems. Figure 1 presents this approach, which was used as starting point for our framework. This enabled us to account for the land resources that were deprived from the natural environment, in order to deliver products for humans. It is important to mention that this system classification regards exclusively to the origin of the resources.

The approach for accounting non-renewable resources consumed (e.g., crude oil) using exergy-based LCIA methods (CExD and CEENE) is through their exergy content, since this is the exergy that is deprived from nature. We understand the same approach should be used for renewable resources originated from natural systems, given that these resources were produced exclusively by nature, i.e., negligible human intervention happened prior to the extraction of

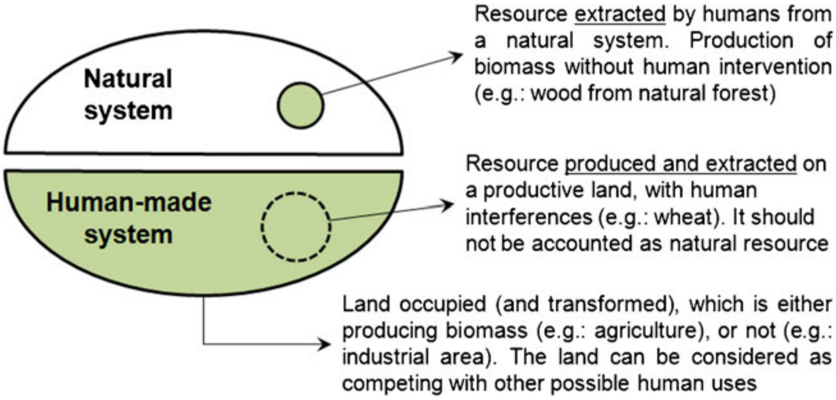


Fig. 1 Schematic representation of land resources from two different systems, regarding their origin

the biomass. In other words, a system can be qualified as natural if the production of its biomass can be maintained with no or negligible human intervention. Human intervention typically means the introduction of operations relying on natural resources from elsewhere (e.g., ploughing and fertilization). Examples of land resources from natural systems are wood harvested from primary forests, seafood from non-modified ocean waters, and grass consumed in extensive pasture lands. Therefore, the land resources from natural systems were set in this paper to be accounted through the exergy content of the biomass extracted. More detailed information about four forest types considered by the authors as natural systems can be found in the Electronic supplementary material (S1).

In human-made systems, the land area has been previously transformed from natural to human-made environment and is being occupied either for non-productive land use (e.g., urbanization), or for a productive land use, with significant human intervention at the production, as agriculture, livestock (intensive pasture), intensive wood production (in forest plantations), fish cultivation (in aquaculture), etc. In these productive land uses, we understand that the actual biomass yield is considered not to be extracted from nature but produced within a human-made system (technosphere); for the authors of this paper, what is actually deprived from the natural environment and/or from other human uses is the land area, next to other natural resources brought to the specific human-made system (e.g., fossil fuels, water, etc.). For this reason, in specific human-made systems, the land occupation was set to be accounted for as land resource competing with other possible human uses. More detailed information on a forest type considered by the authors as human-made system can be found in the Electronic supplementary material (S1).

Unlike natural systems, where the biomass content is directly expressed in terms of exergy, land occupation by human-made systems cannot. In Brehmer et al. (2008) and in the CEENE method (Dewulf et al. 2007), the solar irradiation available for photosynthesis is used as a proxy for land occupation, since this solar exergy is no longer available to nature. However, the photosynthetic solar exergy may not be a consistent indicator for the resource value of land (especially when spatial-differentiation is sought), since other factors are not taken into account, such as climate and soil quality. The natural potential net primary production (NPP), which is the amount of NPP a land area would produce if it was not occupied by humans (Erb et al. 2009; Haberl et al. 2007), can be used as a better proxy to represent the resource value of land. It considers several local natural conditions, such as solar exergy, soil quality, water availability, temperature, among others, allowing spatial-differentiation in a consistent way. In this sense, the potential NPP is a more representative base to quantify land for specific human-made systems in exergy terms.

2.2 Characterization factors

In order to make impact assessment methods operational for LCA, the elementary flows that ought to be used in the life cycle inventory (LCI) (e.g., emission of CO_2) need to receive a value representing the degree of its impact on the environment, so-called CF (International Organization for Standardization (ISO) 2006).

Starting from the framework set in Fig. 1, CF of land resources from natural systems were derived from the content of the biomass extracted from the land. We considered the chemical exergy value (CEV) of the biomass in subject to express the exergy content, which can be calculated through several methods (Szargut et al. 1988). According to Vries (1999), it is preferable to consider the group contribution method, since it is more accurate than the β-low heating value (LHV) method and others. In LCI databases, the biomass characteristics are typically expressed by their amount harvested (kg or m^3) and/or their energy content, which is usually the high heating value (HHV). Therefore, CF shall be calculated through correlations between the biomass' CEV (MJ_{ex}) and its HHV (MJ) or quantity (kilograms or cubic meters). Since the water content in biomass can differ considerably between species, we prefer to make a ratio between CEV and HHV where possible, in order to generate the CF for natural systems (Eq. 1):

$$CF_{\mathrm{natural}} = CEV(MJ_{\mathrm{ex}})/HHV(MJ) \qquad (1)$$

For land resource CF in human-made systems, we set to account for the land occupation, based on potential NPP. As source of data, we used Haberl et al. (2007), allowing the generation of site-generic and site-dependent $\mathrm{CF}_{\text{human-made}}$ (at continent, country, region, and grid level). NPP in Haberl et al. (2007) is represented in mass of carbon (kilogram carbon), and to transform it into exergy units, we calculated biomass-exergy conversion factors ($\mathrm{MJ_{ex}}$/kilogram carbon) for specific natural vegetations. First, the Earth's land was divided into different biomes. We used 13 of the 14 biomes from Olson et al. (2001) excluding mangroves, since it is a biome that mixes water and land surfaces. Then, we partitioned the biomes' NPP into above- and belowground biomass. For tundra, we used the data from Shaver and Chapin (1991), and for desert and grasslands (five different types), we used the data from Hui and Jackson (2006). For forests biomes, we divided the NPP into roots, woods, and leaves, by using the data from Luyssaert et al. (2007). To obtain the chemical composition of the biomes' vegetation with its typical species, we used the Phyllis database (Phyllis 2011), except for data on grass roots, where we used data from (Saunders et al. 2006). We proceeded with the exergy calculations, applying the group contribution method or the β-LHV method. More information on the calculations can be found in the Electronic supplementary material (S2). As a result, we obtained conversion factors for each of the 13 biomes, and further on, we calculated a single average. Then, we multiplied the value of each pixel from the map from Haberl et al. (2007) by the appropriate conversion factor (Eq. 2).

$$\begin{aligned}\mathrm{CF}_{\mathrm{human-made}} &= \mathrm{Potential\,NPP}\left(\mathrm{kgC}/\mathrm{m^2 year}\right)\\ &\quad\times \mathrm{Conversion\ factor}\left(\mathrm{MJ_{ex}}/\mathrm{kgC}\right)\end{aligned} \qquad (2)$$

In the map generated, each pixel had a specific average value for potential NPP ($\mathrm{MJ_{ex}}/\mathrm{m^2}$year/pixel), which is the site-dependent CF at grid level. Since the map was drawn through equidistant cylindrical projection, the area of a pixel on the map gets higher than it is in reality when moving toward the poles. Because of that, average values for specific regions may not be representative for large areas. Therefore, to draw the site-dependent CF (at region, country, and continent level), we multiplied the potential NPP value of each pixel by its real surface area, then we summed these values within the region we intended to have CF and divided it by the sum of the real surface areas of the pixels from the same region, generating area-weighted average values.

2.3 Practical implementation

We implemented the CF produced in this paper into practical conditions, divided in two levels. First, on a CF level, we intended to check the framework and the CF produced, in comparison to other LCIA methods that account for land resources by the same system boundaries. Then, on an overall resource footprint level, we intended to check the share of land resources in products from existing LCI databases and the effects of regionalization on final results. These practical implementations were done through case studies.

For the first level, we applied the CF (from human-made and natural systems) into a case study of wood production systems, in which data for land resources were based on processes from ecoinvent database v2.2 (Ecoinvent 2010). The functional unit was the production of 1 $\mathrm{m^3}$ of wood (at forest road). For natural systems, we considered the production of Meranti and Azobe woods in Malaysia and Cameroon respectively (Althaus et al. 2007). For human-made systems, we selected the production of eucalyptus in Thailand and Parana Pine in Brazil (Althaus et al. 2007). Then, we compared the results with other LCIA methods: CED, CExD, and CEENE. More information on the LCI of the land resources consumed in this case study, based on the ecoinvent database, can be found in the Electronic supplementary material (S3). This wood production case study was applied with the purpose of illustrating the differences on accounting for land resources in human-made and natural systems, by different LCIA methods, and was named "case study 1".

For the second level, first we implemented the CF into ecoinvent database elementary flows, although we were able to apply only the site-generic CF, since this LCI database does not support (yet) site-dependent CF. After that, we included these CF in the elementary flows from *Land Occupation* (*and transformation*) category and the biotic portion of the *Renewable Resources* category in the CEENE method. For all other natural resources (fossil fuels, water, metals, and minerals), we relied on the original CF from the CEENE method. Then, we applied this customized CEENE method into a case study of human-made biomass products, using nine biomass production processes from ecoinvent database v2.2 (the name of the processes can be seen in the Electronic supplementary material (S4)) and summed up all natural resources with the same unit, as done in the original CEENE method. Besides the site-generic CF, we also applied site-dependent CF (at continent, country, and regional level) for the direct land occupation. With this case study, named "case study 2", we could evaluate the share of land resources in comparison to the overall natural resource footprint and how spatial differentiation on land resources can affect the final result of an overall resource-based LCIA method.

3 Results and discussion

3.1 Characterization factors

3.1.1 CF of land resources in natural systems

Given that land resources from natural systems are quantified by the exergy content of the biomass harvested, site-generic $CF_{natural}$ were based on calculations by Dewulf et al. (2007), where the exergy/energy ratios had less than 2 % difference among species, with a final average value equal to 1.06 MJ_{ex}/MJ.

3.1.2 CF of land resources in human-made systems

$CF_{human\text{-}made}$ were obtained from the land occupation, based on potential natural NPP. We obtained a biomass-exergy conversion factor of 42.9 MJ_{ex}/kgC, which is the average value of the 13 biomes' conversion factor, with a coefficient of variance of 0.02. Then, we multiplied the values of the potential NPP map by the biomass-exergy conversion factor. As a result, we obtained a map with potential NPP in exergy units, with a grid size of 5′ geographical resolution (approximately 10 × 10 km at the equator) that was used to generate the $CF_{human\text{-}made}$ (Fig. 2). Figures of maps with larger scales can be found in the Electronic supplementary material (S5). The ASCII file of this map can be downloaded from the link in the Electronic supplementary material (S6).

Site-generic and site-dependent CF (at continent, country, region, and grid level) for human-made systems were produced through the values from this map. A site-generic CF (world average) and site-dependent CF at continent level can be seen in Table 1. We calculated site-dependent CF at country level for 163 countries and site-dependent CF at regional level (administrative regions) for the six largest countries in area (Russia, Canada, China, United States, Brazil, and Australia). The full list of site-dependent CF (at country and regional level) can be seen in the Electronic supplementary material (S7).

As it can be seen in Table 1, the average characterization factors are considerably different from each other, for instance, South America has an average CF value that is almost two times higher than North America. Besides that, except for Europe, the standard deviations are rather high. Therefore, whenever possible, it is better to use the site-dependent CF, at country, region, or grid level, which can be found in the Electronic supplementary material (S6) and (S7), for more precise values.

NPP as a quantifier for obtained products/outputs in intensive agriculture, forestry, or other human-made systems has already been used in other LCIA methods, mainly to quantify ecosystem quality rather than for resource accounting (Baitz et al. 2000; Beck et al. 2010; Lindeijer 2000; Nakagawa et al. 2002; Weidema and Lindeijer 2001). It is also used by the HANPP indicator (Erb et al. 2009; Haberl et al. 2007) that considers the potential natural NPP and agricultural yields to account for the human appropriation of NPP. Contrary to them, the method proposed in this paper, which is designed for resource accounting in LCA, uses the potential natural NPP to account for the consumption of

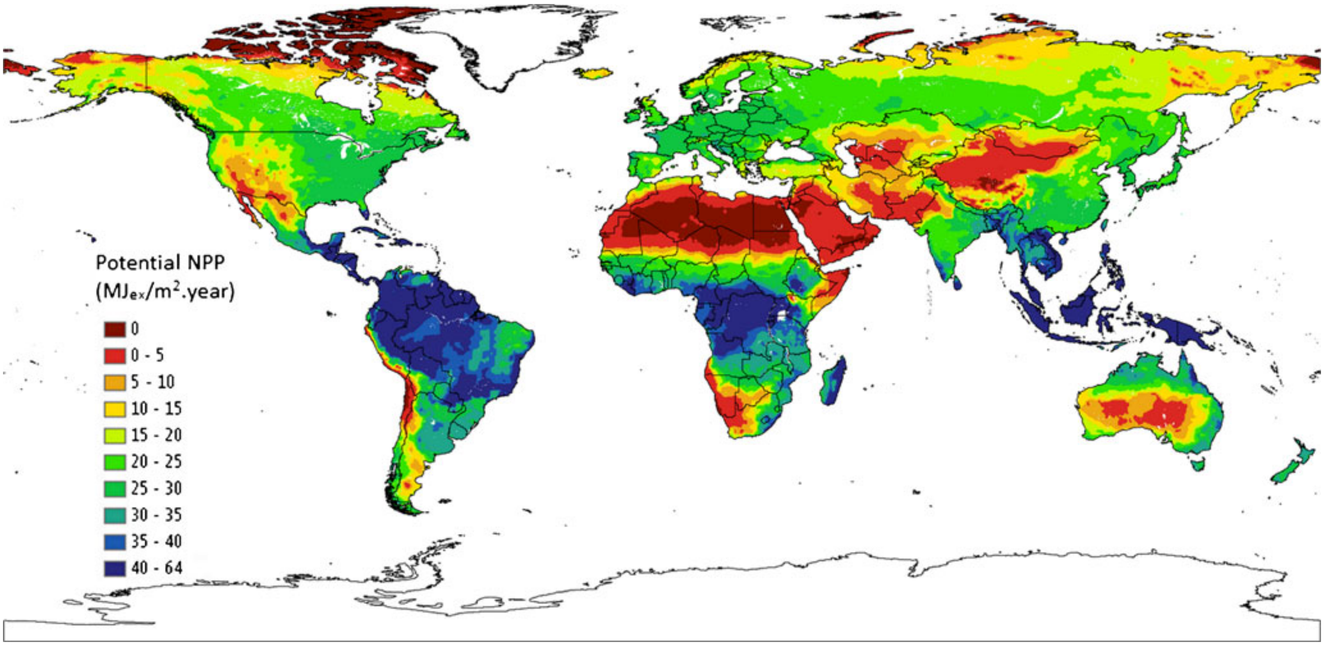


Fig. 2 World map of characterization factors of land resources in human-made systems, based on the potential availability of natural net primary production (in exergy units, MJ_{ex}/m^2year)

Table 1 Characterization factors for land resources (at continent level and world average), in human-made systems, with the variability of values within each area

Continent	Characterization factors (MJ_{ex}/m^2year) Mean value	Variability of the values (MJ_{ex}/m^2year)	
		2.5th percentile	97.5th percentile
World	21.5	0.0	48.2
North America, Central America, and Caribbean	19.8	0.0	39.9
South America	35.6	4.3	51.3
Europe	23.2	11.7	29.2
Africa	19.8	0.0	48.8
Asia	18.1	0.0	47.8
Oceania and Australia	18.0	2.1	35.0

natural land resources of human-made systems. In this sense, agricultural yields are not considered since they are technosphere outputs. In fact, our approach concentrates on how to quantify the value of land as natural resource, next to others (e.g., fossil, metals, and minerals). This is one specific aspect of land. Of course, land use means also other environmental impacts next to resource use (e.g., loss of biodiversity), which need to be evaluated by other specific midpoint categories (e.g., de Baan et al. 2012).

The uncertainties for the CF generated in this study, for human-made systems, can come basically from two sources: (1) the general exergy-biomass conversion factor and (2) the potential NPP values, obtained from Haberl et al. (2007). For the former, according to Vries (1999), the group contribution method is more precise than the β-LHV, but in some situations there were no data available to proceed calculations by the first method. The CEV of wood ("Wood, oriental beech", from Phyllis database) can have a coefficient of variation of 3 % if performing calculation by the two methods mentioned above. Besides, there are already embedded uncertainties on the chemical composition of the vegetation, obtained mainly from Phyllis database. Regarding the second source, uncertainties may come from the model used (Wang et al. 2011; Lauenroth et al. 2006; Jenkins et al. 1999) and also from considerations on the input data for the model, as climate and leaf area index (Williams et al. 2001). Coefficients of variation on NPP values can range from 40 % to 163 %, depending on the model used (Lauenroth et al. 2006). The potential NPP values from Haberl et al. (2007) were calculated by using the Lund–Potsdam–Jena dynamic global vegetation model. Consequently, other values of potential NPP could be obtained if another model was used.

3.2 Practical implementation

3.2.1 Case study 1

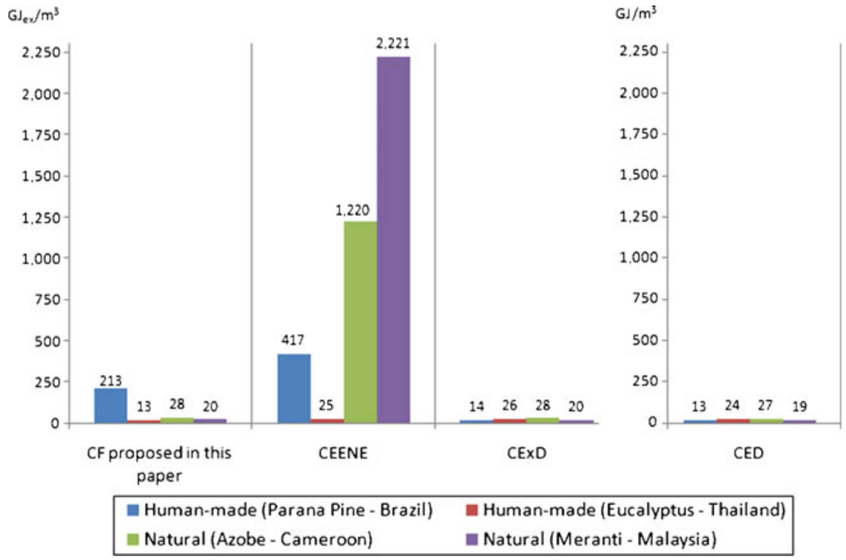
In this case study, we used the site-generic $CF_{natural}$ (1.06 MJ_{ex}/MJ) for the products from natural systems. For the Brazilian Parana Pine, we used the site-dependent $CF_{human\text{-}made}$ at regional level for the state of Parana (34.8 MJ_{ex}/m^2year; Supporting information S7); and for the eucalyptus, we used the site-dependent $CF_{human\text{-}made}$ at country level for Thailand (36.0 MJ_{ex}/m^2year; Electronic supplementary material (S7)). The CF used in the other LCIA methods can be seen in Hischier et al. (2009) and Dewulf et al. (2007). Figure 3 shows the result of this case study.

By using the CF proposed in this paper, the eucalyptus from Thailand (human-made system) had the lowest land resource consumption (13.1 GJ_{ex}/m^3), mainly due to its short growth cycle (see Fig. 3). Opposite to that, the Parana Pine from Brazil (also from human-made system) had the highest land resource consumption (212.7 GJ_{ex}/m^3). The woods from natural systems presented values in between those two (28.0 and 20.2 GJ_{ex}/m^3) and were function of the wood quality, i.e., the exergy content of the wood species (Azobe and Meranti).

Figure 3 shows that the CEENE method gave extremely high values to the natural systems, due to the extensive way the biomass is produced (1.2×10^3 and $2.2\times10^3 GJ_{ex}/m^3$). The ratio between the highest and lowest land resource consumption for 1 m^3 of wood is in the order of 90 (2.2×10^3 versus 24.5 GJ_{ex}/m^3, respectively) in this method. On the other hand, the CExD method produced more equal results, since only the exergy of the biomass is taken into account: Different yields do not affect the final result. The difference between its highest and lowest values is in the order of 2 (27.8 and 13.7 GJ_{ex}/m^3, respectively). The CED method produced similar results to the CExD method, since both of them consider only the content of the wood.

Overall, a considerable diversity among the impact assessment methods was noticed, especially between the CEENE and the CExD. Although they have the same basic scientific concept (exergy), their results were unlike, due to their different choices in what to account for land resources. The CF proposed in this paper account for land resources in two different ways, combining the strengths of the CExD and the CEENE methods (biomass exergy content is taken

Fig. 3 Result for case study 1 with the CF proposed in this paper, two exergy-based LCIA methods and an energy-based LCIA method



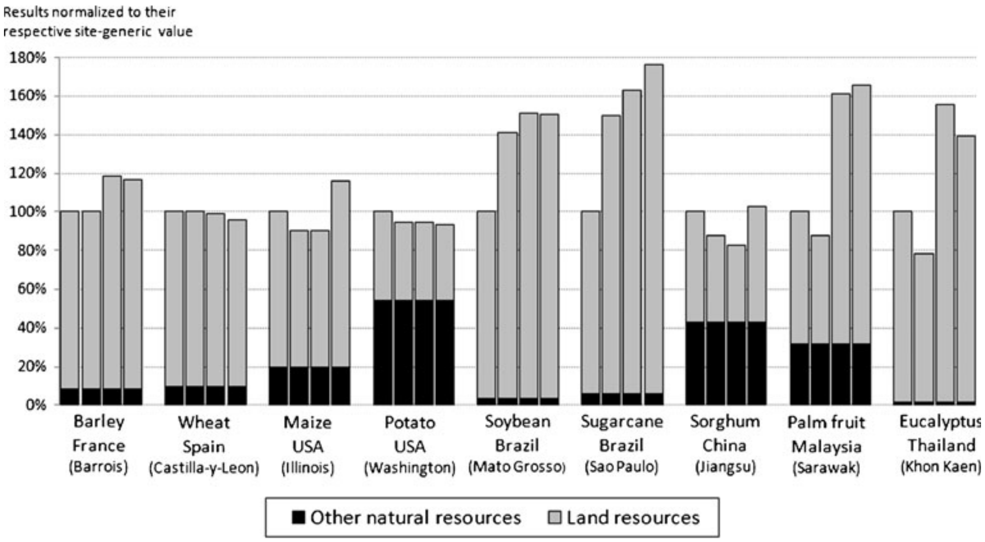
as a starting point for the use of land resources at natural system, while the exergy related to the deprived natural potential NPP is used for accounting land resources at human-made systems). Even though the initial distinction between natural and human-made systems may sometimes not be straightforward (e.g., at natural forests), the method proposed in this paper is able to avoid double-counting of land resources, since the exergy content of the biomass and the exergy deprived from nature due to land occupation shall not be accounted together.

3.2.2 Case study 2

To perform the analysis on nine biomass products from ecoinvent (all human-made systems), first we applied the site-generic CF into the elementary flows from ecoinvent. The former database does not support completely the framework proposed in this paper, so small adaptations had to be performed while implementing the CF. A list of the elementary flows from ecoinvent, adjusted to the framework proposed in this paper, is presented in the Electronic supplementary material (S8). Next, we considered also the site-dependent CF (at continent, country, and regional level), as presented in the Electronic supplementary material (S7), for the direct land occupation, i.e., only for the foreground data. For all nine of them, we specified a region ourselves (seven cases), or it was specified by the ecoinvent database (products from France and Spain). Figure 4 shows the results of this comparison.

The land resources are represented in gray color, and all the other natural resources (non-biotic renewable resources, metals, minerals, fossil fuels, nuclear energy, water resources, and atmospheric resources) are represented in black color. From Fig. 4, we can see that the share of land

Fig. 4 Comparison between site-generic (*outer left bars*), site-dependent at continent level (*middle left bars*), site-dependent at country level (*middle right bars*), and site-dependent at regional level (*outer right bars*) CF for nine biomass products, showing the share of land resources in the overall resource footprint and how their spatial-differentiation can affect the final results



resources can be very high for the products with high renewability degree (Dewulf et al. 2005), e.g., 97 % for soybeans from Brazil (site-generic CF). On the other hand, potatoes from the USA, sweet sorghum from China, and palm fruit from Malaysia had a high share of other natural resources (54 %, 43 %, and 32 %, respectively), especially water, since they are irrigated systems. These results show how land resources play an important role in the overall resource footprint of a product.

In a next step, natural resource consumption for all nine cases were intended to be site-dependent; however, in practice only, the land resources from human-made systems could be made site-dependent, relying on the CF brought forward with this paper. Except for wheat from Spain, which site-dependent CF value is similar to the site-generic CF, the variation on the final result is considerable, either giving a lower value (down to 78 % for eucalyptus in Thailand, when using site-dependent CF at continent level), or making it increase up to 177 % (for sugarcane in Brazil, when using site-dependent CF at regional level). Another important aspect shown in Fig. 4 is the direct relation between the variation of the final results due to regionalization with the renewability degree, e.g., the value of the site-dependent CF (at regional level) for Malaysia is higher than for Brazil (Supporting information, S7), but the variation in the final results with the site-generic CF was lower (166 %, while for sugarcane in Brazil was 177 %). This happened because 32 % of the total exergy value from Malaysian palm fruit is from non-land resources, making the regionalization of land resources less influential in the final result than in the Brazilian sugarcane case.

From these results, we could observe how the use of site-generic data can underestimate (e.g., palm fruit from Malaysia) or overestimate (e.g., potatoes from USA) the overall resource used. The CF proposed in this paper has the novelty to generate site-dependent CF at different levels (for land resources from human-made systems).

4 Conclusions

By clearly distinguishing between natural and human-made systems, we are able to consistently account for land resources that are actually extracted/deprived from the natural environment and/or competing with other possible human uses. Site-dependent CF for human-made systems allow spatial differentiation in the exergy calculations for LCA, which was excluded so far. A future challenge is the development of regionalized CF for other natural resources (e.g., water and metals) in exergy terms, in order to give a complete overview on regionalization of resource consumption.

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