

1 **Global land use impacts on biomass**
2 **production flow – a spatial-differentiated**
3 **resource-related life cycle impact assessment**
4 **method**

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1 ABSTRACT

2 *Purpose:* In life cycle assessment (LCA), the impact assessment on natural resources is
3 still in the early stages of research, and the impacts of biotic resources are usually not
4 evaluated. The human appropriation of net primary production (HANPP) is a well-known
5 indicator of land use impacts, but it cannot be easily implemented in LCA. The objective
6 of this paper was to create a life cycle impact assessment (LCIA) method on land use
7 impacts on net primary production (NPP), based on the HANPP approach.

8 *Methods:* To create an operational LCIA method, the midpoint characterization factors
9 (CF) were calculated by comparing the NPP of plants occurring under current land uses
10 with a baseline scenario, i.e., the NPP of potential natural vegetation. For the endpoint CF
11 we considered the backup technology concept, and included in the calculation the
12 marginal cost for additional biomass production through algae cultivation in the ocean.

13 *Results:* Site-generic and site-specific midpoint and endpoint characterization factors
14 (CF) were created in a global scale, for 164 countries, and for four types of land uses
15 (cropland, pasture, infrastructure, and wilderness). For cropland we also created biomass-
16 specific CF for ten particular crops in a global scale. The LCIA method was tested in
17 particular case studies, and seemed to produce comparable results, with the possibility of
18 coupling it with other LCIA methodologies, as Recipe Endpoint.

19 *Conclusions:* The LCIA method proposed in this paper provides an assessment of the
20 decrease of biomass availability due to land use (affecting the AoP Resources), which is
21 an impact category poorly considered in LCA. Nevertheless, the method has some future
22 challenges, for instance to take into account site-specific backup technologies for the
23 endpoint CF.

24

25 *Keywords:* LCA, land use, biomass, resource, method

1. INTRODUCTION

Humans need resources for their everyday life, e.g. cooking, transportation, heating, etc. The high population growth, especially during the last 50 years (United Nations 2013), together with the increase in consumerism, motivated concerns related to the use and extraction of natural resources, especially when considering the natural constraints of the Earth. Sustainable development, as defined by United Nations (1987), is a *development which meets the needs of current generations without compromising the ability of future generations to meet their own needs*. In this sense, the use, extraction and also depletion of natural resources become very important issues in our society.

In Life Cycle Assessment (LCA) the environmental impacts on natural resources are evaluated in the area of protection (AoP) named Resources (ISO 2006). The impacts in this AoP are usually evaluated at three levels of life cycle impact assessment (LCIA) methods (Swart et al. 2014; European Commission 2011): (1) Resource Accounting Methods (RAM), as the Cumulative Exergy Extraction from the Natural Environment (Dewulf et al. 2007) and the Cumulative Energy Demand (Hischier et al. 2009); (2) Midpoint level, e.g. Abiotic Depletion Potential from CML (Guinée 1995); and (3) Endpoint level, as evaluated in Eco-indicator 99 (Goedkoop and Spriensma 2000) and Recipe Endpoint (Goedkoop et al. 2009). The most straightforward correlation between environmental interventions and impacts on the AoP Resources is the link between consumption-depletion, i.e., due to the consumption of a certain resource, it may be depleted. However, there are other causes for resource depletion, e.g., climate change, acidification, and land use. Similarly, the consumption of certain resources (e.g. water), i.e., an environmental intervention, can cause impacts on other AoP (e.g. human health) (Pfister, 2009). Nevertheless, the environmental impacts on this AoP are still considered to be not well-defined (Hauschild et al. 2013), leaving several scientific gaps to be tackled.

LCIA methods evaluating the impacts on Resources at the first level, i.e., RAM, usually provide completeness since they consider most of the natural resources (e.g. metals, fossils, land, water, etc). However, they are often criticized for analyzing solely the consumption/use of natural resources, and not their depletion and other environmental impacts (Hauschild et al. 2013; European Commission 2011). The LCIA methods evaluating at midpoint and endpoint levels consider the depletion of natural resources, but just of a certain group of natural resources, i.e., most of them evaluate the depletion of metals and fossils (Swart et al. 2014; European

1 Commission 2011; Hauschild et al. 2013). There are some recent works on depletion of other
2 types of resources, as Pfister et al. (2009), Frischknecht et al. (2009), and Milà i Canals et al.
3 (2009) for water scarcity, and Núñez et al. (2013) for soil depletion due to erosion. Nevertheless,
4 LCIA methods for other types of resources than fossils and metals at midpoint and endpoint level
5 are still at early stages of development.

6 The impacts on biotic resources at the AoP Resources have been assessed in LCA mainly at the
7 first level of assessment, i.e., through RAM. Even though biotic resources are renewable, they can
8 still be depleted (as water). Biotic resources can be depleted mainly by two impact pathways: (1)
9 permanent reduction of the biomass stocks; and (2) reduction on the biomass production flow, or
10 the net primary production (NPP) (Figure 1). Typical examples of impacts on permanent reduction
11 of the biomass stocks are deforestation and overfishing. However, this impact pathway is beyond
12 the scope of this paper. For the impacts on NPP, they can have several reasons, e.g. climate change
13 and ecotoxicity, but they may also be due to land use, i.e., the management activities humans
14 undertake in a certain type of land to make use of it (FAO 1997), which can cause positive or
15 negative impacts on NPP. On top of that, land use can cause several other impacts, and much
16 effort has been devoted recently to include such impacts in LCA, e.g. land use impacts on
17 biodiversity (Koellner and Scholz 2008; Schmidt 2008; Michelsen 2008; de Baan et al. 2013),
18 erosion (Núñez et al. 2013), ecological quality of the soil (Mila i Canals et al. 2007; Saad et al.
19 2013), and soil fertility for crop production (Brandão and Mila i Canals 2013). Yet little research
20 has been devoted to scrutinize land use impacts on biomass production flow (i.e., NPP) at the AoP
21 Resources. This type of assessment has been studied in the works of Haberl et al. (2007) and Erb
22 et al. (2009) with the Human Appropriation of Net Primary Production (HANPP). The HANPP
23 seemed to represent well the impacts on NPP due to land use, and some studies tried to link it with
24 LCA (Alvarenga et al. 2013a,b; Haberl et al. 2009), although this method cannot be easily
25 implemented completely in LCA studies (Mattila et al. 2012; Zhang et al. 2010) mostly for having
26 different goals than LCA.

27

28 **Fig. 1** Simplified impact pathway on the Area of Protection (AoP) Resources, with the gray area
29 within the dotted lines representing the scope of this manuscript on land use impacts on net
30 primary production (NPP), affecting resource depletion

31

1 The LCIA method proposed by Brandão and Mila i Canals (2013) uses the loss of soil organic
2 carbon as a proxy to evaluate the impacts on the potential of biomass production in different soils.
3 The goal of this method was to evaluate land use impacts on the potential of that land to produce
4 biomass (e.g. agriculture), and it has close relation with impacts on soil fertility. However, it does
5 not evaluate the impacts on biomass production flow (or NPP) due to different land uses. The
6 LANCA tool (Beck et al. 2010) evaluates the biotic production flow of particular land uses,
7 through mass of biomass produced per unit area and time period, i.e., the NPP of that land type.
8 However, it does not consider the increase or decrease of NPP in comparison to a baseline system,
9 e.g., potential natural vegetation (PNV) (Tüxen 1956; Chiarucci et al. 2010).

10 The objective of this paper was to create an LCIA method that evaluates the impacts on biomass
11 production flow (or NPP) due to land use on the AoP Resources. Based on the HANPP method,
12 and through its intermediate indicator ΔNPP_{LC} , we created an operational LCIA method for land
13 use impacts on NPP, at midpoint and endpoint level, with site-generic and country-specific CF.
14 This LCIA method is compatible with existing LCIA methodologies, such as Recipe Endpoint.
15 Finally, the relevancy of our new LCIA method was tested for a number of case studies. The use
16 of NPP as an indicator for land use impacts on life support functions has been criticized in Mila i
17 Canals et al. (2007), since its value can be affected by many other factors, as fertilizers and
18 weather. In other words, it does not represent well issues of soil quality. However, apart from
19 using NPP as proxy to represent soil quality, this indicator can be used as instrumental value for
20 impacts on alterations on biomass production flow, which is the scope of this paper.

21 **2. MATERIAL AND METHODS**

22 **2.1 Framework and characterization factors**

23 NPP is an indicator of the yearly (or another time frame) biomass production of an ecosystem,
24 usually represented by amount of dry matter (DM) or carbon (C) per unit of land occupation, i.e.,
25 time and area ($\text{kgDM}/\text{m}^2\text{a}$ or $\text{kgC}/\text{m}^2\text{a}$, respectively). The HANPP method evaluates how
26 intensively a defined land is exploited by comparing the natural potential NPP of that area with
27 how much NPP is left for the natural environment. For the latter, the actual NPP of that land use is
28 accounted and subtracted the amount harvested for human purposes. The difference between the
29 natural potential NPP and the NPP left for the natural environment is the HANPP. Another way to

1 calculate the HANPP is through the sum of the NPP harvested with the $\Delta\text{NPP}_{\text{LC}}$, which is the
2 difference between the natural potential NPP and the actual NPP. (Haberl et al. 2007; Erb et al.
3 2009).

4 In this manuscript we distinguish between two cases: (1) the NPP of the currently prevailing
5 vegetation under current land use, with or without human intervention, for example infrastructure
6 areas, agricultural land, natural or managed grasslands, natural or managed forests or wilderness
7 area, is called in this manuscript as ‘actual NPP’; (2) the NPP that would occur on the land in the
8 hypothetical absence of direct human intervention but under current climate, i.e., the NPP of the
9 PNV, is called in this manuscript as ‘natural potential NPP’. The difference between the actual
10 NPP and the natural potential NPP is denoted as $\Delta\text{NPP}_{\text{LC}}$, as in Haberl et al. (2007), as represented
11 in Figure 2.

12 **Fig. 2** Representation of the $\Delta\text{NPP}_{\text{LC}}$ indicator, which is the difference between the natural
13 potential NPP and actual NPP

14

15 NPP (and potential NPP) has already been used as proxy for damage assessment in the AoP
16 Ecosystems, as in Nuñez et al. (2013) and Pfister et al. (2009), due to its correlation with damage
17 on vascular plant species biodiversity (Pfister et al. 2009). However, in this study we focused on
18 the use of this indicator for damage assessment in the AoP Resources.

19 The CF for midpoint level is represented by the $\Delta\text{NPP}_{\text{LC}}$, as shown in equation 1, where i is the
20 location (e.g. France) and j is the land use (e.g. pasture or maize cultivation), in $\text{kgDM}/\text{m}^2\text{a}$.

$$21 \quad \text{CF}_{i,j}(\text{midpoint}) = \Delta\text{NPP}_{\text{LC } i,j} = [\text{Natural potential NPP}_{i,j}] - [\text{Actual NPP}_{i,j}] \quad (1)$$

22 To create spatial-differentiated CF we used the natural potential NPP from Haberl et al. (2007),
23 combined with data reported in Erb et al. (2007) to obtain these values for specific land uses
24 (within each country). Actual NPP for cropland, pasture land, infrastructure land, wilderness, and
25 forest were produced based on data for the year 2000, following the methodology described in
26 Haberl et al. (2007). This method systematically combines statistical data (e.g. from FAO) with
27 results from a dynamic global vegetation model and integrates these data in a consistent (between
28 national statistics and remote-sensing derived patterns) and comprehensive (global closed budget,
29 wall-to-wall representation) Geographic Information System (Erb et al. 2007). For cropland, actual

1 NPP was extrapolated from harvest statistics, while for the other land use types it was derived
2 from potential NPP using factors to account for effects of degradation, irrigation, fertilization and
3 soil sealing (Erb et al. 2009; Haberl et al. 2007). We also calculated actual NPP for certain specific
4 crops, based on data from FAO (2013) also for the year 2000. We considered the top six crops in
5 global production quantity and the top six crops in global area harvested in the World (FAO 2013),
6 i.e., wheat, maize, rice, soybean, sugarcane, barley, potato, sorghum, and sugar beet; but also oil
7 palm fruit due to its environmental relevance shown in recent studies. The number of crops is less
8 than twelve because some of them were in the top six for both production quantity and area
9 harvested, as wheat.

10 The midpoint CF can be positive or negative. In the first case, it means that natural potential NPP
11 is higher than the actual NPP, thus less (total) biomass is produced under that particular land use
12 than in a baseline system, established as the PNV. The second situation, when the CF is negative,
13 means that the actual NPP is higher than natural potential NPP, thus the current land use is making
14 more biomass available than in the baseline system. The sign (positive or negative) has the same
15 direction of other LCIA methodologies, i.e., positive means an environmental impact and negative
16 means an environmental benefit.

17 To determine CF on endpoint level, we based on the backup-technology concept, which is the
18 technology applied to use outputs as resources (recycling) but also the alternative technology
19 applied when reaching the ultimate quality limit of a certain resource (Stewart and Weidema
20 2005). This concept is used in more endpoint LCIA methods: (1) in eco-indicator 99 and in Pfister
21 et al. (2009), it is the extra amount of energy required for the backup technology ($\text{MJ}_{\text{surplus}}$); (2) in
22 the Recipe Endpoint it is the extra cost of the backup technology (US\$). However, to derive a
23 backup technology to produce biomass is not as straightforward as for fossil energy carriers or for
24 freshwater production. Biomass productivity (and NPP) can be increased by several management
25 practices, as crop rotation, higher fertilizer (nitrogen) application, water management (irrigation,
26 drainage), etc. These practices depend on several local constraints, as climate and type of crop,
27 making it a hard task to find one single backup technology that could be applied to all types of
28 land uses. For instance, it may be more technically, environmentally, and economically efficient to
29 increase productivity in pasture lands by using the rational grazing management practice described
30 in Voisin (1959) and Machado (2010) than using irrigation, but this technique is not applicable in

1 other types of land uses (e.g. cropland). On top of that, in areas with shortage of nutrients it might
2 be more efficient to increase productivity by increasing fertilization, while introducing irrigation
3 systems may be the best choice for dry regions. In the other hand, biomass availability through
4 intensive algae cultivation has increased in the last couple of years, with different applications
5 (e.g., biofuels and animal feed). In order to make an operational LCIA method, we considered a
6 simplified and site-generic backup-technology for all types of land use, i.e., relying on seaweed
7 production (*Laminaria digitata*) in the ocean. We used its cost per DM as the unit for the endpoint
8 indicator, based on Edwards and Watson (2011), where the costs of seaweed production in the
9 Atlantic Ocean is calculated to be between US\$ 10.00 and US\$ 19.00 per kgDM, at 15% of DM
10 (considering a currency conversion of US\$0.75/€ for the year 2010). We considered the average
11 value, i.e., US\$14.50. Thus the CF for endpoint was calculated based on equation 2, with units in
12 US\$*/m²a. The endpoint CF can be positive or negative, and the rationale of that is the same as
13 previously explained in the midpoint CF section. The cost of seaweed production can vary at
14 different locations and with different technologies, but due to lack of available data we considered
15 solely the value of US\$14.50/kgDM.

$$16 \quad CF_{i,j}(\text{endpoint}) = \Delta NPP_{LC,i,j} \times 14.50 \quad (2)$$

17 For both midpoint and endpoint indicators we produced CF at four levels: (1) Site-generic,
18 biomass generic (S_GB_G); (2) Site-specific (at country level), biomass generic (S_SB_G); (3) Site-
19 generic, biomass-specific (S_GB_S); and (4) Site-specific (at country level), biomass-specific (S_SB_S).
20 CF at S_GB_S and S_SB_S levels were produced solely to the agricultural crops previously mentioned,
21 i.e., wheat, maize, rice, soybean, sugarcane, barley, potato, sorghum, sugar beet, and oil palm fruit.

22 **2.2 Application in case studies**

23 We wanted to test the applicability of our LCIA method, so we applied it into different datasets of
24 the ecoinvent database v2.2 (Ecoinvent 2010). Since this method should be used for all types of
25 products, we did not restrict it solely to agriculture-based products. Also, in order to illustrate its
26 relevancy at the AoP Resources, we coupled our method to the Recipe methodology, producing
27 comparable endpoint results with fossil and metal depletion. We chose some datasets from

* The value of US\$ is based on the year 2010

1 ecoinvent database, based on a diversity of products and spatial coverage (more information about
2 these datasets can be obtained in particular reports from ecoinvent database):

- 3 • The production of Barley grains in western Spain (dataset: *Barley grains conventional,*
4 *Castilla-y-Leon, at farm/ES*). For that we used $S_S B_S$ CF for barley production and $S_G B_G$
5 for all other elementary flows;
- 6 • The production of maize in the United States of America (USA) (dataset: *Corn, at*
7 *farm/US*). For that we used $S_S B_S$ CF for maize production and $S_G B_G$ for all other
8 elementary flows;
- 9 • The production of wheat grains in eastern France (dataset: *Wheat grains conventional,*
10 *Barrois, at farm/FR*). For that we used $S_S B_S$ CF for wheat production and $S_G B_G$ for all
11 other elementary flows;
- 12 • The production of sheep in USA (dataset: *Sheep for slaughtering, live weight, at*
13 *farm/US*). For that we used $S_S B_G$ CF for pasture land (used for sheep grazing) and $S_G B_G$
14 for all other elementary flows;
- 15 • The production of petrol with 5% of its volume with ethanol, and its provision in a gas
16 station in Switzerland (dataset: *Petrol, 5% vol. ethanol, from biomass, at service*
17 *station/CH*). For that we used $S_G B_G$ for all elementary flows;
- 18 • The production of high-density polyethylene in Europe (dataset: *Polyethylene, HDPE,*
19 *granulate, at plant/RER*). For that we used $S_G B_G$ for all elementary flows;

20 All of the case studies are cradle-to-gate LCA, i.e., they stop at the production stage. In this sense,
21 we were not able to evaluate the contribution of the different life cycle stages of the manufactured
22 products, in comparison to the whole life cycle impact.

23 **3. RESULTS AND DISCUSSION**

24 **3.1 Characterization factors**

25 CF for cropland were generated at $S_G B_G$, $S_S B_G$, $S_G B_S$ and $S_S B_S$ (the two latter only for 10 crops).
26 For pasture and infrastructure we created CF only for $S_G B_G$ and $S_S B_G$, i.e., we did not consider
27 biomass-specific CF. For wilderness the actual NPP may be considered as equal to the natural
28 potential NPP, for simplification, thus the CF is equal to zero. For forests, due to lack of data in

1 changes in NPP from forestry management worldwide, it was not possible to generate consistent
2 actual NPP, thus we were not able to calculate CF. As all midpoint CF are multiplied with the
3 same factor to come to endpoint scores, results are similar for the latter and only midpoint results
4 will be discussed at this section. The entire list of midpoint and endpoint CF can be seen in the
5 supplementary material (SM-1 and SM-2, respectively).

6 The midpoint S_{BG} CF for 164 countries for cropland, pasture, and infrastructure can be visualized
7 in Figure 3a, 3b, and 3c, respectively. As we can see, negative values (which mean actual NPP
8 higher than the natural potential NPP) are mostly in dry climate countries (e.g., Egypt) or countries
9 with high crop yields (e.g. France). The highest impacts on NPP were determined for tropical wet
10 countries, mainly influenced by rather high natural potential NPP values. The results for pasture
11 lands were similar to croplands, i.e., countries with dry climate or countries with a high share of
12 intensive pasture land production had negative results (positive impacts). In contrast, for
13 infrastructure areas all countries had positive values, meaning that the actual NPP in those land
14 uses were always lower than the natural potential NPP. Also, countries with dry climates had the
15 lowest CF for infrastructure, mainly due to low natural potential NPP (i.e., a low amount of
16 biomass is deprived to give place for infrastructure areas).

17 The CF calculated for cropland, pasture, and infrastructure varied substantially among the
18 countries. In figure 4a the box-plots (with 95% of confidence interval) show the highest variability
19 for cropland, followed by infrastructure areas, and then by pasture lands. Figure 4b represents the
20 variability among the ten different crops, which was rather high for some crops, as maize and
21 sugarcane, while for other crops (e.g. soybean and barley) the variability was rather low. The main
22 reason for that was the high range of actual NPP from certain crops among the countries, as
23 sugarcane and maize (11.45 kgDM/m^2 and 8.56 kgDM/m^2 , respectively), in comparison to the low
24 range of actual NPP from other crops, as soybean and barley (1.30 kgDM/m^2 and 2.78 kgDM/m^2 ,
25 respectively), while the range of natural potential NPP was constant ($2.52 \text{ kgDM/m}^2\text{a}$).

26 The variability on cropland and pasture land was caused by a combination of low/high actual NPP
27 with high/low natural potential NPP, while the variability on infrastructure areas was caused
28 mainly by differences in natural potential NPP. For pasture lands just a few cases (between the 75
29 and 95 percentiles) generated negative values (Figure 4a), which were in countries with high share

1 of intensive and/or irrigated pasture lands. On average, sugarcane appears to be the crop with the
2 best results for NPP (median CF = $-4.47 \text{ kgDM/m}^2\text{a}$), but there are situations in which other crops
3 have better results than sugarcane (Figure 4b). This elucidates that not only the type of biomass
4 produced is important when analyzing land use impacts on NPP, but also where it is produced.

5

6 **Fig. 3** Characterization factors of biomass-generic data for 164 countries for (a) cropland, (b)
7 pasture lands, and (c) infrastructure areas

8

9 **Fig. 4** Box-plot (95% confidence interval) of the variability of the characterization factors per land
10 use (a) and per crop type (b)

11

12 **3.2 Application to case studies**

13 We applied our LCIA method into six case studies (based on datasets from the ecoinvent
14 database); both for the midpoint and endpoint CF. Moreover we also calculated the environmental
15 impact on other types of resources for these six datasets, using the Recipe methodology. The
16 results of the midpoint analysis can be seen in Figure 5, while the results for the endpoint analysis
17 can be seen in Table 1.

18

19 **Fig. 5** Result of the $\Delta\text{NPP}_{\text{LC}}$ at midpoint level for the six datasets (reference flow = 1 kg)

20

21 The results show that the LCIA method proposed in this manuscript is applicable to different types
22 of products. In some cases the results were negative (for maize production in USA and wheat
23 production in France), meaning that these crops improved the overall NPP. Production of barley in
24 Spain and production of sheep in USA had positive results, mainly meaning that the actual NPP of
25 barley and pasture land were lower than the NPP of PNV. The results of petrol in Switzerland and
26 polyethylene in Europe had positive results because all the CF used were S_{GBG} , which are positive
27 for infrastructure, pasture land, and crop-generic (SM-1 and SM-2). It is interesting to note that the
28 magnitude of the impact from polyethylene was rather low, mainly because 1 kg of that product
29 requires much less land occupation than 1 kg of the other products.

1 Due to lack of resource-related LCIA methods on land use impacts using NPP as indicator, we
2 were not able to compare these results with others from literature. Even though the method from
3 Nuñez et al. (2013) uses NPP as proxy for the AoP Ecosystem, we could still use it [to](#) compare our
4 results at midpoint level, since they are both represented by NPP. However, this was not possible
5 because ecoinvent database (the source of the data from our case studies) does not provide
6 information on soil organic carbon loss, data needed to apply that method (Nuñez et al. 2013).

7

8 **Table 1** Impact in the AoP Resources for the six cases studies, representing the $\Delta\text{NPP}_{\text{LC}}$ and the
9 Recipe Endpoint methodology for fossil and metal depletion (reference flow = 1 kg)

10

11 The $\Delta\text{NPP}_{\text{LC}}$ was applicable to the six case studies at endpoint level as well. The results had the
12 same trend for midpoint results, i.e., negative values for maize in USA and wheat in France, and
13 positive values for the others. The [interpretation of](#) backup technology units might seem difficult
14 to interpret, but considering the case of barley produced in Spain ($\Delta\text{NPP}_{\text{LC}} = \text{US\$ } 0.575/\text{kg}$) it
15 means that less overall biomass is being made available on Earth in comparison to the PNV, and in
16 order to compensate that loss of 1 kg of biomass, US\$ 0.575 would be spent to produce the
17 shortage of biomass through algae cultivation.

18 We adjusted the currency for metals and fossil resources from the year 2000 to the year 2010 by
19 considering a cumulative inflation rate of 26.6% (USIC, 2014). Even though water depletion at
20 endpoint level (in $\$/\text{m}^3$) has been recently operationalized and made compatible with Recipe
21 Endpoint (in ecoinvent version 3.0), we did not considered it in our study, that used an earlier
22 version of ecoinvent database (v2.2). Fossil resources were the main contribution for polyethylene,
23 while for the other products it was mainly $\Delta\text{NPP}_{\text{LC}}$. This predominance of higher $\Delta\text{NPP}_{\text{LC}}$ in
24 comparison to fossil and metal may be due two reasons: (1) Except for petrol, the other products
25 are mainly land-based, thus it would be expected that the most striking resource would be biomass;
26 (2) the extra costs through the backup technology for $\Delta\text{NPP}_{\text{LC}}$, i.e., algae cultivation, might indeed
27 be more expensive per unit of mass produced than the backup technology for fossil energy and
28 metals.

1 Nevertheless, the main focus of this section was to verify the application of $\Delta\text{NPP}_{\text{LC}}$ into different
2 case studies and to test if it could be integrated with other endpoint indicators affecting the AoP
3 Resources. In this sense, we can see that $\Delta\text{NPP}_{\text{LC}}$ can generate results in the same unit than other
4 endpoint indicators, being possible to integrate them into a single score result for the AoP
5 Resources.

6 **3.3 Outlook and future challenges**

7 We provide a method to quantify land use impacts on biomass production flow (or NPP), on a
8 midpoint as well as an endpoint level, thereby providing the opportunity to compare biotic
9 resource depletion with abiotic resource depletion. By comparing our method with metal and fossil
10 depletion indicators (at endpoint level) we could observe the significance of the $\Delta\text{NPP}_{\text{LC}}$
11 assessment in comparison to other resources. Environmental impacts on $\Delta\text{NPP}_{\text{LC}}$ have been
12 neglected so far in LCA at endpoint level, most of them overlooking the natural potential NPP that
13 already exists on that particular land, without land use.

14 Our method has some uncertainties, for instance: (1) the costs of the backup technology can
15 become spatial-differentiated and land use specific. For instance, more data on costs for algae
16 production could be considered and/or costs for increasing productivity in pasture land can be
17 based on best local techniques (irrigation, fertilization, etc); (2) even though the natural potential
18 NPP has grid-specific data, the CF of this LCIA method were available solely up to country-
19 specific level, since the worldwide actual NPP values for specific crops were restricted to that
20 level. This uncertainty could be reduced if crop yields with better resolution were used (Monfreda
21 et al. 2008); (3) The model and the input data used for the calculation of the natural potential
22 NPP has some uncertainties (Williams et al. 2001; Lauenroth et al. 2006; Wang et al. 2011); (4)
23 The extrapolation of data from harvested biomass to total above- and belowground biomass is
24 sometimes rather generic (Haberl et al. 2007); (5) The actual NPP for cropland, based on data from
25 FAO (2013), is published on amount harvested per area, and to include the time factor, i.e., to
26 account for time in the yield ($\text{kgDM}/\text{m}^2\text{a}$), we had to make assumptions on multicropping
27 (considering the production of more than one crop in the same area during one growing season for
28 some countries where this is possible) and fallow. The datasets of Haberl et al. (2007) and Erb et
29 al. (2007) refer to physical areas, in contrast to harvested areas as used by FAO (each land unit is

1 counted as often as it is harvested). The difference between physical area and harvested area are
2 lands left idle (fallows) in cases where physical hectares are larger than harvested areas, and, in the
3 opposite case, indicate multicropping (i.e. more than one harvest cycle in a calendar year); (6) The
4 marginal cost for biomass production of seaweed is based on only one study, due to lack of data on
5 this topic; (7) There is no biomass differentiation, since they are treated as the same (in mass of
6 dry matter). One way to deal with this issue could be to recalculate the CF based on exergy terms
7 (Dewulf et al. 2007; Dewulf et al. 2008), which can be interpreted as a challenge left by this paper.

8 Another challenge left by this paper is the goal to improve the AoP Resources. As mentioned by
9 Hauschild et al. (2013), the environmental impacts on this AoP are still considered to be not well-
10 defined. The impacts are mainly focused on the resource depletion, but the LCA community lack
11 on variety of other midpoint categories affecting this AoP, for instance alterations on biomass
12 production flow (introduced by this paper), but also other categories, as changes in provisioning
13 services that may not directly cause resource depletion (e.g. water competition), and the
14 anthropogenic stocks and recyclability of metals (Klinglmair et al. 2014). Ideally, these midpoint
15 impact categories should be grouped into a single endpoint indicator (e.g. MJ_{surplus}), giving more
16 completeness to the AoP Resources. On top of that, CF for more specific land uses should be
17 calculated, for instance, for different agriculture techniques (organic, irrigated, no tillage, etc).

18 As previously mentioned, biotic resources can be depleted basically by two impact pathways: (1)
19 permanent reduction of the biomass stocks; and (2) decrease on the net primary production (NPP).
20 Our method focuses on the latter, since we could not find available data for the assessment of the
21 former. Therefore, a future challenge left by this manuscript is to develop an operational LCIA
22 method for land use impacts on AoP Resources through permanent reduction of the biomass
23 stocks. One approach for that would be to evaluate it through land transformation (or land use
24 change) elementary flows for human-made systems and through biotic resource extractions for
25 natural systems (Alvarenga et al. 2013**b**).

26 **4. CONCLUSIONS**

27 This paper proposed a new LCIA method to evaluate the impacts on NPP due to land use, based
28 on the HANPP approach, making use of the $\Delta\text{NPP}_{\text{LC}}$ indicator. The LCIA method is made
29 operational with site-generic and site-specific CF for four land use types (cropland, pasture,

1 infrastructure, and wilderness) and with biomass-specific values as well for cropland. It is easily
2 applicable in LCA, since the user of this method has solely to classify (at the life cycle inventory)
3 the type of land use in one of those four aforementioned types, and for the case of cropland, also
4 specify which type of crop. It was applied into different case studies to test its applicability,
5 generating comparable results. The ΔNPP_{LC} LCIA method can be further improved in the future,
6 for instance considering more detailed data for the costs of the backup technology.

7 The proposed LCIA method allows a more complete overview on the impacts at the AoP
8 Resources, since it allows comparable results with other types of resources, as metals, fossil
9 energy carriers, and water. Through that, certain land-based products (e.g. biofuels) become
10 subject to resource depletion for their feedstock as well, and not only for their utilities (e.g. diesel
11 consumed during harvest), as commonly accessed in LCA.

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