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Which Species Count? Reflections on the Concept of Species Richness for Biodiversity Endpoints in LCA

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The importance of Life Cycle Assessment (LCA) as an impact assessment tool has been growing in recent years. There are important mandates in place that provide incentives for companies to use this method to quantify the environmental impacts of their activities, and more are expected to follow. There are, however, some significant challenges that must still be addressed before the method becomes established practice. One of the most important barriers remaining is finding a widely accepted and accurate impact assessment method for biodiversity.

This review article presents a reflection on the concept of species richness as it is currently used in Life Cycle Impact Assessment methodologies. It applies to calculations of biodiversity impacts from land use exclusively. Power law models such as the Species-Area Relationship are useful macroecological tools to predict potential extinctions from land use due to their apparent simplicity and broad applicability.

The main assumptions of the SAR models are laid out and their limitations critically assessed when used in the context of LCA. Alternatives models are proposed for future evaluation by Industrial Ecologists and Biologists. The article also proposes a rationale under which a model can be considered to fit LCA's purpose, and finally conclude with a shortlist of topics for future research.

1. Introduction

Life Cycle Assessment (LCA) is an impact assessment tool aiming to evaluate potential impacts of the production, use, and waste management of goods and services (Tukker, 2000). It started as an academic tool but now it is recognized as a major strategic management and decision-making tool by businesses (Verdantix 2011). The product-level LCA market in the European Union was worth $27.9 million in 2011, and is expected to grow 31-45 % per year to reach 103.3 M$ by 2015 (Verdantix 2012). There are several pending mandates that may take LCA even further towards becoming part of business practice. The French government recently ran a pilot for a labelling program for consumer goods; LCA was the method chosen to calculate indicators displayed in labels (ADEME-AFNOR, 2013). The European Commission (EC) is also running a pilot to test Product Footprint Guidelines (EC, 2013) with guidance to calculate environmental indicators using LCA for assertive comparisons between products and organizations.

Before LCA can fulfil the objectives purported it must address significant objections to the reach and validity of its methodological framework and indicators. One of the most important challenges regards the inclusion of good metrics for biodiversity impacts (Freidberg, 2013), and particularly impacts occurring due to land use and land use change. These impacts are not yet satisfactorily included in the LCA framework (Teixeira, 2014). Biodiversity is relevant for products in all sectors, due to its double value; biodiversity has existence value – as a value to preserve in human activities (Guidi et al., 2009) – and use value to humans – for example as a source of materials for productive processes (Molina et al., 2012). The inherent complexity of this double role of biodiversity makes it more difficult to devise indicators for this multifaceted, highly specific and local phenomenon.

In order to improve the way Life Cycle Impact Assessment (LCIA) addresses biodiversity impacts from land use, one must first understand how developers of assessment methods solved this problem thus far. Species diversity is a key component in the current paradigm for the operationalization of characterization

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factors (CF) in LCIA for land use (Koellner et al., 2013). Biodiversity change from species diversity is calculated as the percentage of species lost per area in a land regime relative to a reference land regime; the percentage of species lost is obtained from the standard Species-Area Relationship (SAR) (de Schryver et al., 2010).

The present is a review article that briefly reflects on the concept of biodiversity as applied in LCA. The following section presents an abridged description of the framework for biodiversity endpoint calculations currently implemented in LCA, focusing on impacts occurring due to land use and land use change. Later, possible alternatives to replace the established SAR model are introduced and assessed for their pertinence and effects to impact assessment characterization factors. A final section studies the implications other models would have in LCA impact assessment models, and propose some open threads that should be addressed in future research.

2. Species-area relationship

2.1 Modelling species richness change with land use

The ISO 14042 (2000) provides guidelines for impact assessment methodologies in LCA. The guidelines were operationalized in the model for species richness dynamics described and discussed in Teixeira (2014). This common impact assessment method uses the framework originally proposed for changes in land quality by Lindeijer (2000) and depicted in Figure 1. The model was later used by de Schryver et al. (2010) to calculate characterization factors in LCA and implemented in ReCiPe, the most widely used LCA methodology today. The model in Figure 1 assumes that land occupation is a one-time, on/off phenomenon during a given time (t) and in a given area (A) that originates an instantaneous decrease in quality (Q) – or increase in loss of quality (-Q) – in area A at t_0. This decrease is sustained until the new occupation is abandoned at t_1, which is when the loss of quality is at its maximum of $-Q_{max}$. The ecosystem then enters a relaxation period during which it regains quality. Q may return to the original level $-Q_0$ (at t_2) or stabilize at a lower Q-level of $-Q_f$. The characterization factor is calculated as the area below the curve.

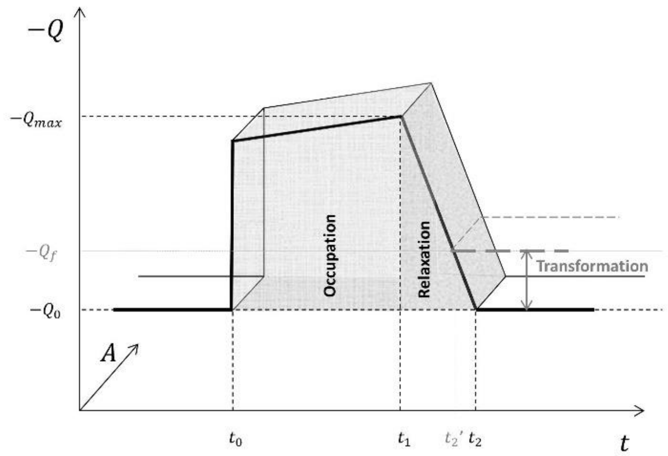

Figure 1: Impacts from land use change on ecosystem quality (adapted from Mila-i-Canals et al., 2007). Variables: -Q – decrease in quality; A – area, t – time; Subscripts: 0 – start of occupation; 1 – end of occupation; 2 – end of relaxation; f – final level; max – maximum level.

The variable Q needs to be further operationalized using a different model that relates Q to biodiversity and defines the functional form that relates Q and A. Biodiversity is measured using species richness (or number of species) as an indicator. That model is described next.

2.2 Basic model

The simplest macroecological model that relates species richness and area is the SAR (Sarkar and Margules, 2002), also known as the Arrhenius (1921) model, shown in Eq(1).

$$S(A) = c.A^z \qquad (1)$$

S(A) is the number of species in area A. The parameter z, conventionally interpreted as the “slope” of the SAR, is a constant in the range of 0.10-0.35, depending on the taxon, scale and land use. It is also referred to as the “species accumulation” factor (de Schryver et al., 2010). Parameter c measures the specific richness of the biome – species naturally occur in greater numbers in some biomes. It is assumed that c is a constant, and so invariant with the area. The SAR thus stipulates that species richness increases with area – if a larger area is sampled, more species are likely to be found (Rosenzweig, 1995). The marginal increase is higher for small areas than for large areas, which can be seen in Figure 2.

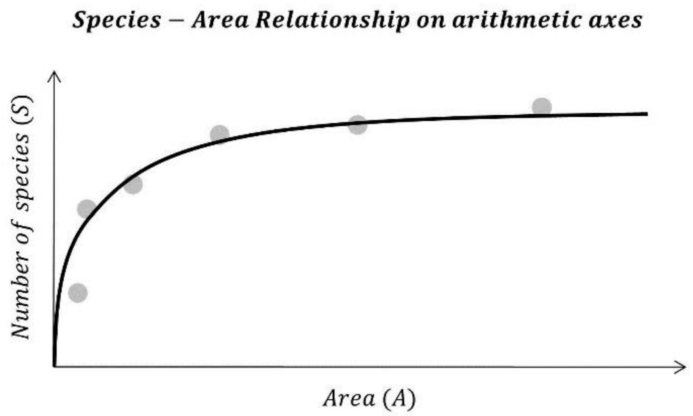

Figure 2: Illustrative graphical representation of the power law species-area curve in Eq(1)

Suppose A_o is the total area of the biome, and S_o the number found in the entire biome of area A_o before a given occupation change. After the change, the natural area remaining is A_f. Aplying the model in Eq(1), the new number of species $S(A_f)$ is given by Eq(2).

$$S(A_f)/S_0 = (A_f/A_0)^z \quad (2)$$

The parameter c influences the number of species left but not the fraction of species left, since the biome is the same.

2.3 The importance of SAR slopes in LCA

As explained by Teixeira (2014), characterization factors in LCA are calculated using the framework described in Section 2.1 above with the SAR as the model that calculates the variation in Q levels. The resulting damage factor is measured in Potentially Disappeared Fraction (PDF) of species multiplied by the duration of the effect (such as land occupation, in the simplest case) and times the area disturbed.

As Eq(2) shows, the disappeared fraction is proportional to the fraction of the area disturbed to the power z. It is this parameter that controls the difference in species richness with land use. Under some conditions, it can be shown that the characterization factor is exactly equal to z or the difference of the z values for the baseline and the new land use systems (for details on the calculation of the characterization factors, see de Schryver et al., 2010).

3. Limitations and alternatives to the basic SAR

3.1 Species-habitat-area curve

Theoretically, there are two main inherent limitations with the SAR when determining effects of land use change on biodiversity (Proença and Pereira, 2013). First, the SAR represents single habitats. “Area” is a homogeneous variable that represents space available to species without any discrimination of its qualities. Habitat richness and characteristics of the surroundings such as genetic diversity and fragmentation are important qualitative proprieties of biomes that are required to describe species diversity but are not captured if their specific dynamics is reduced only to an area. As a consequence for LCA, characterization factors calculated with the SAR run into difficulties to accurately identify correct conservation priorities in biodiversity hotspots or places of biological interest.

To overcome this limitation, Triantis et al. (2003) proposed a Species-Area-Habitat Relationship (SAHR) affirming that habitat diversity can “replace” area. A smaller area loss in a diverse ecosystem can represent the same number of species lost as a higher area loss in a less diverse one. The model is shown in Eq(3).

$$S(A_f)/S_0 = (A_f.H_f/A_0.H_0)^z \quad (3)$$

This model fits well to small islands or isolated environments. There is evidence that ecosystems proprieties influence the loss of species richness after land use change. However, the model introduces the complexity of defining "habitat diversity", which is a highly specific parameter. This model is thus less parsimonious than the SAR.

The second limitation mentioned above is that in the eyes of the SAR all species are equal. The SAR also takes all species into account regardless of their status as endemics, exotic or invasive. More importantly, there is no differentiation of the diversity of species responses to land use changes. There is a whole spectrum of responses to habitat change, ranging from species that are highly sensitive to habitat loss to species that even benefit from the conditions found in human-modified habitats (Proença et al., 2010). For brevity, this line of enquiry is not pursued in this article (for models that deal with this topic, please see Proença and Pereira, 2013).

3.2 Endemics-area curve

There are also practical limitations of the SAR due to its inherent simplicity. Predicting species extinctions with the SAR is mostly a matter of estimating z, which is typically done adjusting a logarithmic version of Equation (2) to data from a given region. There are other related functional forms that adjust better to the data – some introducing new parameters (for a review of some forms that have been proposed and their test, see Dengler, 2009). There are also more complex methods that use matrix effects (Koh and Ghazoul, 2010), some of which have even already been translated into LCA damage factors (Baan, 2013).

In particular, several authors failed to validate the SAR and found that it consistently overestimates species extinctions (He and Hubbell, 2011). Kinzig and Harte (2000) proposed an Endemics-Area Relationship (EAR) that has the opposite form of the SAR – meaning that interventions in small areas will have lower species loss because the probability of finding an endemic species (one which cannot be found elsewhere in the biome) is lower when smaller areas are sampled. The EAR has been receiving great appraisal, and some authors consider it a more realistic alternative to the SAR (Rahbek and Colwell, 2011) – although the conclusion that the SAR overestimates extinctions has been disputed (Rybicki and Hanski, 2013).

The EAR has a similar functional form as the SAR but considers only regionally endemic species. On a regional scale (larger plot), the accumulated number of species is the same – but the slope is steeper since for smaller plots the likeliness of finding endemic species is lower. The EAR typically predicts lower species loss for small scale land use changes (as is common for product LCA).

3.3 Implications for LCA

LCA deals with *potential impacts*. It is not the exact impact that takes place that matters, but rather how a given product or process ranks in a comparison with other products and processes or itself (when testing changes to its life cycle).

Suppose we consider two species-area models A and B. Model A is more complex than Model B (uses more parameters and requires more data and spatial resolution, which means it is computationally much more expensive). Assume that this idealized Model A captures biodiversity dynamics exactly as it occurs on the field. Model B has the following property: A is related to B in such a way that applying A and B to any two products 1 and 2 will always lead to the same result in terms of which product has the highest impact. In other words, if $B(1) > B(2)$, then $A(1) > A(2)$ for any 1, 2.

In that case, even if A is more accurate, model B is sufficient for practical use in LCA – because if product 1 causes higher impacts *in reality* on biodiversity (as measured with A), it necessarily also causes higher *potential* impacts (as measured with B). If this is true for an idealized Model A that corresponds exactly to reality, it must (due to transitivity) apply also to all other models in between (in what concerns accuracy) A and B.

The conclusion is that what LCA aims to find is the simplest model that, despite finding potential disappeared fractions different from real disappeared fractions of species, still identifies activities that are more likely to increase extinction risk. It is therefore not the case that the most accurate model should be used, but rather *the most parsimonious model that conserves the hierarchical structure of impacts*.

Some of the models considered above are unlikely to provide different results. Models which are linear transformations of the standard SAR curve can be discarded. Others are more challenging to assess. The SAHR and the EAR are two examples of models that should be applied thoroughly to determine if there are differences in characterization factors. The habitat heterogeneity factor introduced in the SAHR has been shown to be reducible to a linear perturbation of the slope of the basic SAR (Kallimanis et al., 2008) for plants, in which case relative results would be conserved by using the model. The SAHR has, however, also been used to determine regional conservation targets with success (Chen, 2009). Its effects on LCA impact assessment are thus unknown.

The slope factors for SAR and EAR are significantly different (Storch et al., 2012), but it is also thus far unknown if the two approaches provide different relative distributions of LCA characterization factors on a pixel-per-pixel basis. There is a mathematical relationship between the EAR and the SAR (Pan, 2013), and both use the same number of parameters, so it is also possible that the two models are equally parsimonious and provide similar (relative) results. However, previous analyses of hotspots of species richness have shown that these are not congruent with endemism or even threat level of species (Orme et al., 2005).
The scale at which the SAR (or an alternative model) is calculated must also be tested. Using a slope factor for smaller regions will provide different results from using a slope factor for a larger region that encompasses the smaller ones – due to the fact that the SAR factors are not linearly related when scales change (Rosenzweig, 1995). The ecoregion approach has been privileged so far in LCA, but it remains an open question whether a different choice would provide different conclusions.
The work presented in this article assumes (without discussing) that species richness can be used as an indicator in LCA for the state of biodiversity and its change due to land use. This article focused on the concepts behind some models available for potential change in species richness with land use only. Note that even when this assumption is fair the question of which species should be considered (and which taxon/taxa) in the models is still an open one – only indigenous species or also exotic ones, for example. The concept of species richness itself also requires more debate, as damage factors are likely to be different depending on the approach.

4. Conclusions

The challenge of integrating biodiversity metrics in LCA transcends the LCA community due to its importance and the magnitude of the challenge, even when biodiversity as a complex and multidimentional phenomenon is reduced simply to species richness dynamics. This article presented several possible ways of modelling species richness, as well as a rationale to confirm or disprove the SAR as a valid modelling approach in LCA. Further work is needed to investigate new open threads regarding other models in need of testing and which species should be considered in the data. It is essential that biologists and ecologists interested in conservation and estimating extinctions and loss of ecosystem services due to human activities join in on the effort of finding the best model to apply to LCA.

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