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Proposing a life cycle land use impact calculation methodology

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Abstract

The Life Cycle Assessment (LCA) community is yet to come to a consensus on a methodology to incorporate land use in LCA. Earlier our research group presented a methodology based on the ecosystem exergy concept. The ecosystem exergy concept suggests that ecosystems develop towards more effective degradation of energy fluxes passing through the system. The concept is argued to be derivable from two axioms: the principles of (*i*) maximum exergy storage and the (*ii*) maximum exergy dissipation. In this paper we present a methodology to assess impacts of human induced land use occupation, in which we make a difference between functional and structural land use impacts. The methodology follows a dynamic multi-indicator approach looking at mid-point impacts on soil fertility, soil structure, biomass production, vegetation structure, on-site water balance and biodiversity. The impact scores are calculated as a relative difference with a reference system. We propose to calculate the impact by calculating the land quality change between the former and the actual land use relative to the quality of the potential natural vegetation. Impact scores are then aggregated, as endpoint impacts, in (*i*) structural land use impact (exergy storage capacity) and (*ii*) functional land use impact (exergy dissipation capacity). For aggregation of the relative mid-point impact scores no characterization factor is used. In order to fit this impact calculation in the LCA framework the end-point impact scores are multiplied by a LCA component, a component that enables us to report the impact per functional unit

Introduction

Human activities have spatial needs for extraction of resources, forestry and agriculture, infrastructure and dwellings, industrial production processes and landfill. The use of land will often make the land unavailable for other uses, but may also change the quality of the land in terms of life support or potentiality for other land use (Heijungs *et al.* 1997; Lindeijer 2000; Lindeijer *et al.* 2002). Land use and land use change are considered by the international community as a significant aspects of global change, which may induce climate change (Kalnay & Cai 2003; Lavy *et al.* 2004), desertification (Lavy *et al.* 2004; Asner & Heidebrecht 2005) and loss of biodiversity and life support functions (Lindeijer 2000; Lindeijer *et al.* 2002; Miles *et al.* 2004; Milà i Canals *et al.* 2007).

Several methods have been developed for the assessment of environmental impacts generated by land use and land use change (e.g. monitoring procedures, standards with principles, criteria and indicators (PC&I), environmental impact assessment (EIA) and life cycle assessment (LCA) (Baelemans & Muys 1998)). These methods and tools still face specific and shared problems regarding the land use impact assessment. Among these problems the selection and definition of relevant and measurable indicators seems one of the most persistent (Baelemans & Muys 1998). Discussions on land use impact in LCA community seem to reveal a lack of consensus on what exactly has to be assessed (Milà i Canals *et al.* 2006; Udo de Haes 2006; Baitz 2007; Milà i Canals *et al.* 2007; Milà i Canals 2007; Milà i Canals *et al.* 2007a). According to the authors the reason for these problems lies in the lack of a solid theoretical concept which can serve as paradigm in which land use and land use change impacts can be evaluated and assessed.

In this paper we plea for the use of the exergy ecosystem concept as founding concept. Based on the insight of this concept, we try to identify the land use occupation (end-points) which should be assessed (also see Peters *et al.* (2003) and García-Quijano *et al.* (2007)). In accordance to land use cause effect chains we propose a universal applicable (mid point) indicator set which will allow us to calculate the end-point impacts.

Background

Ecosystem exergy concept

The ecosystem exergy concept suggests that ecosystems develop towards more effective degradation of energy fluxes passing through the system (Dewulf *et al.* 2008). The concept is argued to be derivable from two axioms: the principles of (*i*) maximum exergy storage and the (*ii*) maximum exergy dissipation (Fath *et al.* 2001). Exergy is the energy that can be converted to work when the system is brought to thermodynamic equilibrium with its environment. Thus, exergy is the entropy-free energy. According the maximum exergy storage principle an ecosystem on any site, with given abiotic features and local gene pool, would develop towards a state of highest possible exergy storage in terms of biomass, genetic information and complex structural networks (Jorgensen & Mejer 1979; Bendoricchio & Jorgensen 1997). The principal of maximum dissipation means that for any site an ecosystem would tend towards maximum dissipation of the exergy influxes (Schneider & Kay 1995). In more ecological terms this could be described as maximization of buffering capacity. In the recent state-of-the-art review article, Dewulf *et al.* (2008) conclude that the ecosystem exergy concepts hosts varied and promising applications (e.g. land use impact assessment), but also state that its premisies and conclusions are still debated (Dewulf *et al.* 2008).

Approach

Indicator selection

Land use was, in the light of impact assessment of land use, by Lindeijer *et al.* (2002) referred to as such intensive human activities, aiming at exclusive use of land for certain purposes and adapting the properties of land areas in view of these purposes.

The authors feel that the ecosystem exergy concept gives good insight in what should be assessed in land use impact assessment. Land use, as defined by Lindeijer *et al.* (2002), has an impact (*i*) on the highest possible level of exergy storage (in terms of biomass, genetic information and complex structural networks) of a certain piece of land. Furthermore land use has impact on (*ii*) the exergy dissipation or buffer capacity of a certain (eco)system as well. Human land use adapts land quality in view of just storing as much exergy as needed for the land use purpose thereby influencing the buffer capacity of the system as well. The authors feel that this reasoning brings us to two end-point impacts of land use: (*i*) a structural impact on the land system, described as the impacts on land quality in terms of biomass, genetic information and complex structural networks which represents the ecosystem exergy content and (*ii*) a functional impact on the land system, described as impacts on land buffer capacity which represents the ecosystem exergy dissipation rate. Since ecosystem exergy content and exergy dissipation rate cannot be directly measured (Dewulf *et al.* 2008), an indicator set (mid-point indicators) is needed to quantify the end-point impacts.

In order to come to a good universal applicable set of mid-point indicators, the mid-point impacts of land use related interventions have to be identified. A simplified overview of these mid-point impacts of land use related interventions based on Köllner (2000), Lindeijer (2000), Lindeijer *et al.* (2002) and Guinée *et al.* (2006) is given in Figure 1. The indicated mid-point impact aspects are non-exhaustive but, according to us, necessary land use aspects which have to be assessed. Notice that we restrict ourselves to the land use interventions as human activities. Each of these identified mid-point impact aspects are categorized to the 'theoretically' or 'conceptually' identified end-point impacts (Structural land use impact or system exergy content and storage capacity and functional land use impact or system exergy dissipation capacity). As such the human land use interventions are linked to the end-point impacts to be assessed.

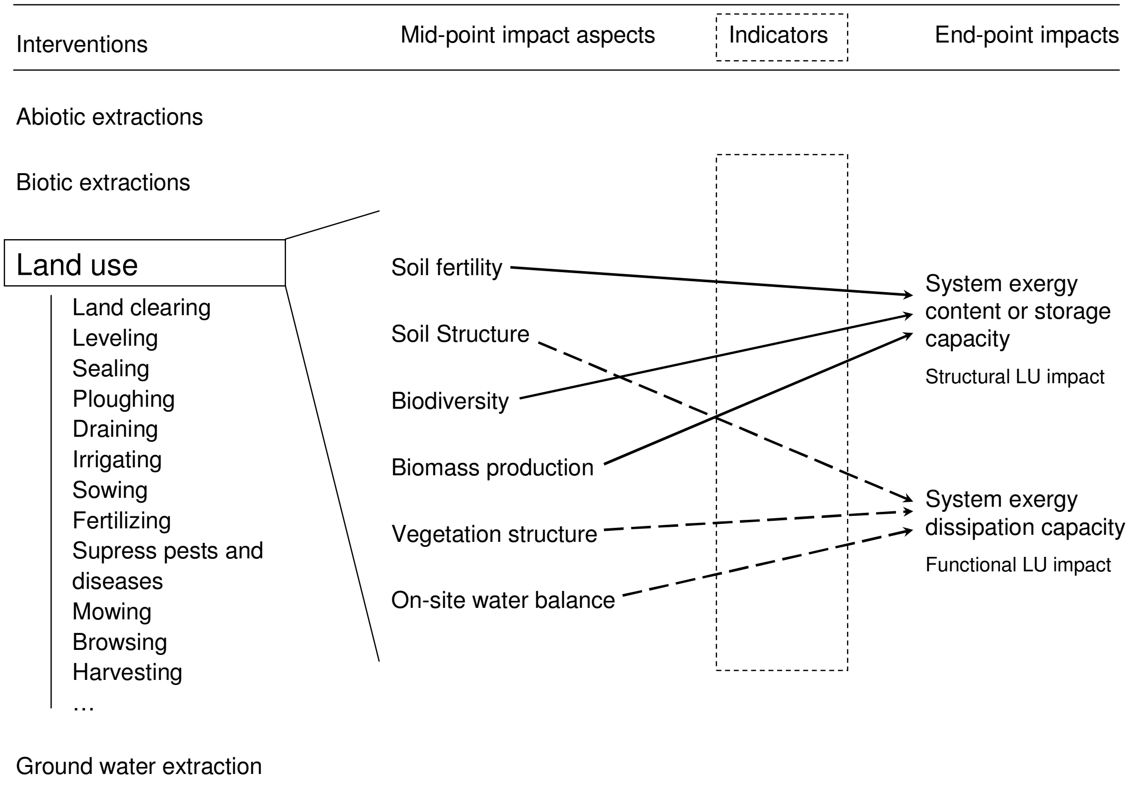


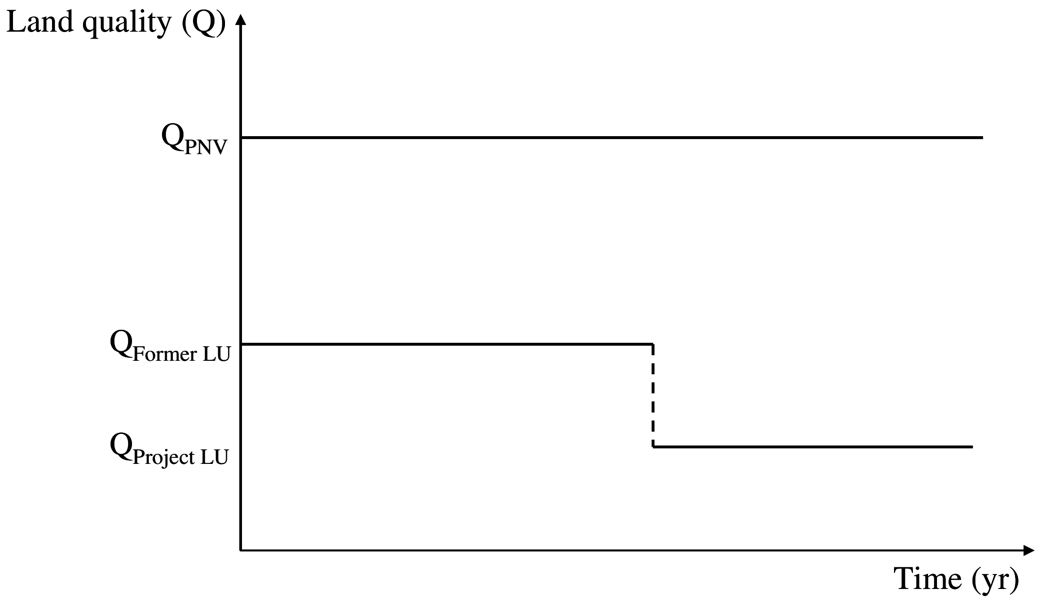
Figure 1. Non-exhaustive overview of mid-point impacts of land use interventions. The arrows show the linkage of mid-point impacts with the end-point impacts.

Soil fertility, biodiversity and biomass production are the mid-point impact aspects of land use necessary to evaluate the structural end-point impact on system exergy content and storage capacity. These three mid-point impact aspects are impacts that will have an effect on the system exergy content (biodiversity, biomass production) or the system exergy storage capacity (soil fertility). The three other impact aspects (soil structure, vegetation structure and on-site water balance) are categorized as functional impacts. Impact on soil structure will result in impacts on the buffer capacity of the system, habitat loss will hamper the system's capacity to dissipate information exergy flows and vegetation structure determines the capacity to dissipate exergy influx from solar radiation. On-site water balance gives an idea of the capacity of a land system to buffer rainfall events.

Note that the identified mid-point impacts actually represent four impact themes: soil, biodiversity, vegetation and water and that all themes, except for water, hold aspects linked both to land system structure and functioning. This is important in indicator selection. Indicators should quantify those aspects of the mid-point impacts that are linked with the end-point impact (see further).

Reference system(s)

The indicator values will give us a valuation of the land quality under a certain land use. An impact on this land quality, caused by human induced land use, has to be measured against a reference system. The authors feel that a new installed land use ('Project LU'), should only be burdened for the change it makes compared to the land use it directly pushed away or will directly push away ('Former LU'), which, as such, should be the reference system. But, since land quality is very site specific, we propose to calculate this burden relative (%) to the maximum potential land quality (Q_{PNV}) (Figure 2). This reasoning will lead us further to an impact indicator calculation method (see further)



$$\Delta Q = \frac{\lfloor Q_{FormerLU} - Q_{ProjectLU} \rfloor}{Q_{PNV}}$$

$Q_{FormerLU}$ as reference. The assessed land use impact is the land quality difference between the project land use and the land use it has pushed or will push away relative to Q_{PNV}.

Figure 2. Simplified depiction of land quality of the new induced land use (Actual LU), former land use (Former LU) and potential natural vegetation (PNV).

Incorporation in LCA

The indicator set and the calculation method will give an environmental impact. From an LCA point of view these impacts should be reported per functional unit (FU) in order to be able to compare scenarios and managements around the world (Heijungs *et al.* 1997). Therefore we present a general formula for land use impact (S) calculation. This formula has two components: impact indicator component (I) and a LCA component (F) (Eq. 1).

$$S = I \times F \qquad \text{Eq. 1}$$

Results

Impact indicator component

Set of indicators

In this section a set of indicators is proposed. This set can be considered flexible. For each mid-point impact aspect two indicators are proposed, except for biodiversity. According to specific situations, specific aims of the user, data availability, measurement feasibility, etc. the users can choose to use both or just one. Further, there is still scope for extra possible indicators per mid-point aspect, according to users' expertise.

Soil fertility

For assessing impact on soil fertility two indicators are proposed: (*i*) cation exchange capacity (CEC) and (*ii*) base saturation (BS) of the topsoil (0-30 cm). CEC has a direct impact on the soil ability to support vegetation and therefore on the ability of the ecosystem to store exergy by producing biomass (Esthetu *et al.* 2004; Rutigliano *et al.* 2004; Bronick & Lal 2005). Loss of BS is considered an impact because it decreases the ecosystem productive capacity and therefore its capacity to store exergy as biomass and genetic information (Hagen-Thorn et al., 2004). Both CEC and BS are directly affected negatively or positively by management practices (Johnson 2002; Favre *et al.* 2002; Lyan & Gross 2005; Asano & Uchida 2005).

Soil structure

Impacts on soil structure can be assessed by: (*i*) soil organic matter (SOM) of the topsoil (0-30 cm) and (*ii*) soil compaction. SOM is an good indicator of the dynamic nature of soils (Milà i Canals *et al.* 2007b) and for the physical and chemical filter and buffer capacity (Milà i Canals 2003). Soil compaction reduces the volume of air in the soil and reduce infiltration rate and as such can have negative impacts on root development and biomass production (Munkholm *et al.* 2005) and increased surface runoff (Jonson-Maynard *et al.* 2002; Green *et al.* 2003). In Fig. 1 the soil structure impact aspect is characterized as impact on system energy dissipation capacity, the calculation of soil compaction indicator will therefore be based on infiltration rate (I) (see further). As such this indicator will highlight changes in the capacity of the ecosystem to buffer water and sediment flows.

Biomass production

Any decrease of biomass due to harvest in any of its forms or by changes in site quality is assumed to cause a decrease of ecosystem control over energy, nutrients and water flows (Mortimore *et al.* 1999; Houghton & Hackler 1999; Son *et al.* 2004; Scheller & Mladenoff 2005; Kettunen *et al.* 2005). Therefore the proposed indicators look at the (*i*) total above biomass (TAB) and (*ii*) free net primary production (fNPP). Net primary production (NPP) is controlled by physical, environmental and biotic factors (García-Quijano & Barros 2005). fNPP is the part of NPP which is not harvested but stays in the ecosystem to fulfil life support functions (Lindeijer 2000).

Vegetation structure

Characterized to system exergy dissipation capacity, the proposed indicators are (*i*) leaf area index (LAI) and (*ii*) vertical space distribution. LAI is a reliable indicator of a systems absorption capacity of solar radiation which is the principal source of exergy (Rascher *et al.* 2004; Dungan *et al.* 2004) and systems reduction potential of kinetic energy from raindrops (Van Dijk & Bruijnzeel 2001; Gomez *et al.* 2001; Pañuelas *et al.* 2003; Anzhi *et al.* 2005). Vertical space distribution, calculated by dividing the canopy height of the dominant stratum of the land use (H) by the number of vertical strata in the land use (S), gives an idea about the vertical structure of the vegetation interface buffering solar radiation, rainfall, wind, among others flows. For the same height of the dominant layer in the vertical structure, a lower number of layers would decrease the optimal or maximum buffer capacity of the ecosystem (Onaindia *et al.* 2004; Will *et al.* 2005; Wehrli *et al.* 2005; Stephens & Gill 2005).

On-site water balance

Here evapotranspiration and soil cover are proposed. Loss of evapotranspiration level indicates a decrease of health and productivity of the ecosystem and a loss of control over energy, water and material flows (Obrist *et al.* 2003; Goyal 2004). Soil cover (0-30 cm above ground level) is seen as an indicator of buffer capacity for raindrop impact and superficial erosion (Morgan 1995).

Species diversity

Based on the same reasoning of data availability as Lindeijer (Lindeijer 2000) we opted for vascular plant species number as sole biodiversity indicator.

Impact indicator score calculation

The impact indicator scores (IS) are calculated by multiplying the relative area of the activity (i.e. area of the activity under evaluation over the total area of the project site) by the difference between the observed indicator value and the indicator value for the reference system, normalized by the indicator value of the potential natural vegetation (PNV) in the region. To express the product in percentage it is multiplied by 100 (Eq. 2)

$$IS = \sum_i \left(\frac{A_i}{A_t} * \frac{\left[Value_{ref} - Value_{proj,i}\right]}{Value_{PVN}} \right) * 100 \qquad \text{Eq. 2}$$

with A_t is the area of the specific activity under evaluation, A_t is the total area of the project site, $Value_{proj,i}$ is the value for the selected indicator for the project land use and $Value_{ref}$ is the value of the selected indicator for the reference system (i.e. former land use).

Table 1 gives an overview of the proposed indicators per mid-point impact aspect and the corresponding score calculation. Indicators and formula are chosen in such way that negative environmental impacts give a positive indicator score.

Table 1. Proposed indicators per mid-point impact aspect and impact score calculation

Mid-point impact aspect	Indicator(s)	Impact indicator score calculation	
Soil fertility	Cation exchange capacity (CEC)	$IS_{Sf} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(CEC_{ref} - CEC_{proj,i}\right)}{CEC_{PNV}} \right) * 100$	Eq. 3
	Base saturation (BS)	$IS_{Sf} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(BS_{ref} - BS_{proj,i}\right)}{BS_{PNV}} \right) * 100$	Eq. 4
Soil structure	Soil organic matter (SOM)	$IS_{Ss} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(SOM_{ref} - SOM_{proj,i}\right)}{SOM_{PNV}} \right) * 100$	Eq. 5
	Soil compactation (Infiltration rate, I)	$IS_{Ss} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(I_{ref} - I_{proj,i}\right)}{I_{PNV}} \right) * 100$	Eq. 6
Biomass production	Total aboveground biomass (TAB)	$IS_{Bp} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(TAB_{ref} - TAB_{proj,i}\right)}{TAB_{PNV}} \right) * 100$	Eq. 7
	Free net primary production (fNPP)	$IS_{Bp} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(fNPP_{ref} - fNPP_{proj,i}\right)}{fNPP_{PNV}} \right) * 100$	Eq. 8
Vegetation structure	Leaf area index (LAI)	$IS_{Vs} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(LAI_{ref} - LAI_{proj,i}\right)}{LAI_{PNV}} \right) * 100$	Eq. 9
	Vertical space distribution (ratio of canopy height of the dominant strata (H) devided by number of strata (St))	$IS_{Vs} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(\frac{H_{ref}}{St_{ref}} - \frac{H_{proj,i}}{St_{proj,i}}\right)}{\frac{H_{PNV}}{St_{PNV}}} \right) * 100$	Eq. 10
On-site water balance	Evapotranspiration (ET)	$IS_{Wb} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(ET_{ref} - ET_{proj,i}\right)}{ET_{PNV}} \right) * 100$	Eq. 11
	Soil cover (SC)	$IS_{Wb} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(SC_{ref} - SC_{proj,i}\right)}{SC_{PNV}} \right) * 100$	Eq. 12

Table 1. Continued

Biodiversity (on site α-diversity)	Species diversty (Number of vascular plant species (NS))	$IS_{\alpha\text{-Bd}} = \sum_i \left(\frac{A_i}{A_t} * \frac{\left(NS_{ref} - NS_{proj,i}\right)}{NS_{PNV}} \right) * 100$	Eq. 13

Based on these impact indicator calculations the impact indicator component for structural and functional land quality change due to land use occupation can be calculated.

$$I_{e\cos ystem-structure} = \frac{\overline{IS_{Sf}} + \overline{IS_{\alpha-Bd}} + \overline{IS_{Bp}}}{3} \qquad \text{Eq. 14}$$

$$I_{e\cos ystem-functioning} = \frac{\overline{IS_{Ss}} + \overline{IS_{Vs}} + \overline{IS_{Wb}}}{3} \qquad \text{Eq. 15}$$

with I the impact indicator component and $\overline{IS_x}$ the average indicator score for mid-point impact aspect *x*. Eq. 14 and 15 will result in relative impacts on the land system structure and land system functioning expressed in percentages.

LCA component

The LCA component (F) is necessary to present the impacts per FU.

$$F = \frac{(time * area)_i}{FU_i} \qquad \text{Eq. 16}$$

Where FU_i is the functional unit of the activity in cluster *i* and $(time*area)_i$ is the area needed to produce a FU_i for a specific period of time.

Discussion

Using the ecosystem exergy concept as a founding paradigm in which we can think about assessing land use impact brings us to two main goal functions of ecosystems on which human induced land use has impacts and brings us to impact aspects caused by human interventions which have to be assessed in order to evaluate impact on those goal functions: (*i*) maximization of exergy storage (in terms of biomass, genetic information and complex structural networks) and (*ii*) maximization of exergy dissipation or buffer capacity of a certain (eco)system. According the identified mid-point impact aspects are the minimum and necessary aspects to be taken up in any land use impact evaluation. Starting the approach from a general founding paradigm makes the proposed end-point impacts and indicator set applicable in different kinds of assessment tools, including LCA, as described in this paper (see LCA component).

The calculation of the land use occupation impact between the reference land use (land use that is removed or will be removed) and the project land use relative to the local PNV results in a non site-specific impact (%). As the impact is actually scaled against the maximum possible, the impact does not contain impacts of land use changes or occupation prior to the land use of interest of the LCA study.

In addition to the LCA component, there is scope to include a time component in Eq. 1. This is an optional but recommended component in case of an impact fluctuating over time. This time component integrates the impact over time, which implies knowledge of how an impacting factor will intervene in the long term dynamics of an ecosystem. Therefore, calculation of this component will depend on the state of knowledge and on data availability.

Earlier versions of the presented method have been tested and compared against other methods in temperate (Belgium), Mediterranean (Spain), subtropical (South Africa) and Tropical (Cameroon) land use systems (Peters *et al.* 2003; García-Quijano *et al.* 2007). The presented method itself is applied in a palm oil bio-diesel system (Vandenbempt 2008).

Conclusion

The exergy ecosystem concept shows to be able to make a solid founding base for land use impact assessment. Started from the two starting axioms we identified two end point impact, which are to be assessed by quantifying a proposed non-exhaustive list of mid point aspects. The same reasoning brings us to a proposed set of indicators which can be used flexibly. By assessing impacts between two human induced land uses relative to the potential natural vegetation results in non site-specific impacts. As such the impacts are comparable in different biotic and abiotic situations. Both earlier examples as the palm oil bio-diesel system show the feasibility of the presented method.

References

Anzhi, W., L. Jinzhang, L. Jianmei, P. Tiefou, and J. Changjie. 2005. A semi-theoretical model of canopy rainfall interception for *Pinus koraiensis nakai*. Ecological Modelling 184:355-361.

Asano, Y. and T. Uchida. 2005. Quantifying the role of forest soil and bedrock in the acid neutralization of surface water in steed hill slopes. Environmental Pollution 133:467-480.

Asner, G.P. and K.B. Heidebrecht. 2005. Desertification alters regional ecosystem-climate interaction. Global Change Biology 11: 182-194.

Baelemans, A. and B. Muys. 1998. A critical evaluation of environmental assessment tools for sustainable forest management. *In* Proceedings of the international conference on Life Cycle Assessment in agriculture, agro-industry and forestry. Dec 3-4, 1998 Brussels, Belgium. Brussels, pp 65-75.

Baitz, M. 2007. We seldom think of what we have, but always think of what we miss. International Journal of Life Cycle Assessment 12:77-78.

Bendoricchio, G. and S.E. Jorgensen. 1997. Exergy as a goal function of ecosystem dynamic. Ecological Modelling 102:5-15.

Bronick, C.J. and R. Lal. 2005. Soil structure and management: a review. Geoderma3-22.

Dewulf, J., H. Van Langenhove, B. Muys, S. Bruers, B.R. Bakshi, G. Grubb, R.A. Gaggioli, D.M. Paulus, and E. Sciubba. 2008. Exergy: its potential and limitations in environmental science and technology. Environmental Science & Technology 42:2221-2232.

Dungan, R.J., D. Whitehead, M. McGlone, R.B. Allen, and Duncan R.P. 2004. Simulated carbon uptake for a canopy of two broadleaved tree species with contrasting leaf habitats. Functional Ecology 18:34-42.

Esthetu, Z., R. Giester, and P. Hogberg. 2004. Historical land use pattern affects the chemistry of forest soils in the Ethiopian highlands. Geoderma 118:149-165.

Fath, B.D., B.C. Patten and J.S. Choi. 2001. Complementarily of ecological goal functions. Journal of Theoretical Biology 208:493-506.

Favre, F., D. Tessier, M. Abdelmoula, J.M. Genin, W.P. Gates, and P. Boivin. 2002. Iron reduction and changes in cation exchange capacity in intermittently waterlogged soils. European Journal of Soil Science 53:175-183.

García-Quijano, J., J. Peters, L. Cockx, G. van Wyk, A. Rosanov, G. Deckmyn, R. Ceulemans, S. Ward, N. Holden, J. Van Orshoven, and B. Muys. 2007. Carbon sequestration and environmental effects of afforestation with *Pinus radiata* D. Don in the Western Cape, South Africa. Climatic Change 83:323-355.

García-Quijano, J.F. and A.P. Barros. 2005. Incorporating canopy physiology into a hydrological model: photosynthesis, dynamic respiration and stomatal sensitivity. Ecological Modelling 185:29-49.

Gomez, J.A., J.V. Giraldez, and E. Ferreres. 2001. Rainfall interception by olive trees in relation of leaf area. Agricultural Water Management 49:65-76.

Goyal, R.K. 2004. Sensitivity of evaporatranspiration to global warming: a case study of arid zone of Rajasthan (India). Agricultural Water Management 69:1-11.

Green, T.R., L.R. Ahuja, and J.G. Benjamin. 2003. Advances and challenges in predicting agricultural management effects on soil hydraulic properties. Geoderma 116:3-27.

Guinée, J., L. van Oers, A. de Koning and W. Tamis. 2006. *In* Life cycle approaches for conservation agriculture. Eds. J. Guinée, L. van Oers, A. de Koning and W. Tamis. Institute of Environmental Sciences - Leiden University, Leiden, the Netherlands, CML report 171, pp

Heijungs, R., J. Guinee and G. Huppes. 1997. *In* Impact categories for natural resources and land use. Eds. R. Heijungs, J. Guinee and G. Huppes. Centre of Environmental Science (CML), Leiden, The Netherlands, CLM Report 138, pp

Houghton, R.A. and J.L. Hackler. 1999. Emission of carbon from forestry and land use change in tropical Asia. Global Change Biology 5:481-492.

Johnson, C.E. 2002. Cation exchange prperties of acid forest soils of the northeastern U.S. European Journal of Soil Science 53:271-282.

Jonson-Maynard, J.L., R.C. Graham, L. Wu, and P.J. Shouse. 2002. Modification of soil structural and hydraulic properties after 50 years of imposed chaparral and pine vegetation. Geoderma 110:227-240.

Jorgensen, S.E. and H. Mejer. 1979. Holistic approach to ecological modeling. Ecological Modelling 7:169-189.

Kalnay, E. and M. Cai. 2003. Impact of urbanization and land-use change on climate. Nature 423:528-531.

Kettunen, R., S. Saarnia, P. Martikainen, and J. Silvola. 2005. Elevated CO_2 concentration and nitrogen fertilization of N_2O and CH_4 fluxes and biomass production of *Pheum pratense* on farmed peat soil. Soil Biology and Biochemistry 37:739-750.

Köllner, T. 2000. Species-pool effect protentials (SPEP) as a yardstick to evaluate land use impacts on biodiversity. Journal of Clearner Production 8:293-311.

Lavy, P.E., M.G.R. Cannell, and A.D. Friend. 2004. Modelling the impact of future changes in climate, CO_2 concentration and land use on natural ecosystems and the terrestrial carbon sink. Global Environmental Change 14:21-30.

Lindeijer, E. 2000. Biodiversity and life support impacts of land use in LCA. Journal of Cleaner Production 8:131-319.

Lindeijer E., R. Müller-Wenk and B. Steen. 2002. Impact assessment of resources and land use. *In* Life-cycle Impact Assessment: Striving towards Best Practice. Eds. H.A. Udo de Haes, G. Finnveden, M. Goedkoop, M. Hauschild, E.G. Hertwich, P. Hofstetter, O. Jolliet, W. Klöpffer, W. Krewitt, E.W. Lindeijer, R. Müller-Wenk, S.I. Olsen, D.W. Pennington, J. Potting, and B. Steen. Society of Environmental Toxicology and Chemistry, Pensacola, FL, pp 11-64.

Lyan, J. and N.M. Gross. 2005. Patterns of plant diversity and plant-environment relationship across three reparian corridors. Forest Ecology and Management 204:267-278.

Milà i Canals, L. 2007. Land use in LCA: a new subject area and call for papers. International Journal of Life Cycle Assessement 12:1.

Milà i Canals L. 2003. Contributions to LCA methodology for agricultural systems. Site-dependency and soil degradation impact assessment. Autonomous University of Barcelona.

Milà i Canals, L., C. Bauer, J. Depestele, A. Dubreuil, R. Freiermuth Knuchel, G. Gaillard, O. Michelsen, R. Müller-Wenk, and B. Rydgren. 2007. Key elements in a framework for land use impact assessment within LCA. International Journal of Life Cycle Assessment 12:5-15.

Milà i Canals, L., R. Clift, L. Basson, Y. Hansen, and M. Brandão. 2006. Expert workshop on land use impacts in life cycle assessment (LCA). International Journal of Life Cycle Assessment 11:363-368.

Milà i Canals, L., R. Müller-Wenk, C. Bauer, J. Depestele, A. Dubreuil, R. Freiermuth Knuchel, G. Gaillard, O. Michelsen, and B. Rydgren. 2007a. Key elements in a framework for land use impact assessment within LCA - Response to Helias Udo de Haes. International Journal of Life Cycle Assessment 12:2-4.

Milà i Canals, L., J. Romanya, and S.J. Cowell. 2007b. Method for assessing impacts on life support fnctions (LSF) related to the use of 'fertile land' in Life Cycle Assessment (LCA). Journal of Cleaner Production 15:1426-1440.

Miles, L., A. Oliver, and O. Phillips. 2004. The impact of global climate change on tropical forest biodiversity in Amazonia. Global Ecology and Biogeography 13:553-565.

Morgan R.P.C. 1995. Soil erosions and conservation. Longman group and J. Wiley & Sons, England.

Mortimore, M., F.M.A. Haris, and B. Turner. 1999. Implications of land use change for the production of plant biomass in densely populated Sahelo-Sudanina shrub-grassland in north-east Nigeria. Global Ecology and Biogeography 8:243-256.

Munkholm, L.J., P. Schjonning, M.H. Jorgensen, and K. Thornp-Kristensen. 2005. Mitigation fo subsoil recompaction by light traffic and on-land ploughing: II. Root and yield response. Soil and Tillage Research 80:159-170.

Obrist, D.V.P.S.J., M.H. Young, J.S. Coleman, D.E. Schorrau, and J.A. Anone. 2003. Quantifying the effects of phenology on ecosystem evapotranspiration in planted grassland mesocosms using EcoCELL technology. Agricultural and Forest Meteorology 112:65-84.

Onaindia, M., I. Dominguez, I. Albizu, C. Gabisu, and I. Amezaga. 2004. Vegetation diversity and vertical structure as indicators of forest disturbance. Forest Ecology and Management 195:341-354.

Pańuelas, J., I. Filella, X. Zhang, L. Llorens, R. Ogaya, F. Lloret, P. Comas, M. Estiarte, and J. Terrada. 2003. Complex spatiotemporal phenological shifts as a response to rainfall changes. New Phytologist 161:837-846.

Peters, J., J. García-Quijano, T. Content, G. Van Wyk, N.M. Holden, S.M. Ward, and B. Muys. 2003. A new land use impact assessment method for LCA: theoretical fundaments and field validation. *In* Life Cycle Assessment in the Agri-food sector. Proceedings from the 4th International Conference. Bygholm, Denmark. 143-156.

Rascher, U., E.G. Bobich, G.H. Lin, A. Walter, T. Morris, M. Naumann, C.J. Nichal, D. Pierce, K. Bil, K. Kudeyarov, and J.A. Berey. 2004. Functional diversity of photosynthesis during drought in a model tropical rainforest - the contributions of leaf area, photosynthetic electron transport and stomatal conductance to reduction in net ecosystem carbon exchange. Plant, Cell and Environment 27:1239-1256.

Rutigliano, F.A., R. D'ascoli and A.V. De Santo. 2004. Soil microbial metabolism and nutrient status in a Mediterranean area as affected by plant cover. Soil Biology & Biochemistry 36:1719-1729.

Scheller, R.M. and D.J. Mladenoff. 2005. A spatial interactive simulation of climate change, harvesting, wind and tree species migration and projected changes to forest composition and biomass in northern Wisconsing, USA. Global Change Biology 11:307-321.

Schneider E.D. and J.J. Kay. 1995. Order from disorder: the thermodynamics of complexity in biology. *In* Wathi s life: the next fifty years. Reflections on the future of biology. Eds. M.P. Murphy and L.A.J. O'Neill. Campridge University Press, Cambridge, pp 161-172.

Son, Y., J.H. Park, M.Y. Yi, H.O. Jin, R.H. Kim, and J.O. Hwang. 2004. Biomass, production and nutrient distribution of a natural oak forest in Central Korea. Ecological Research 19:21-28.

Stephens, S.L. and S.J. Gill. 2005. Forest structure and mortality in an old growth Jeffrey pine mixed conifer forest in north-werstern Mexico. Forest Ecology and Management 205:15-28.

Udo de Haes, H.A. 2006. How to approach land use in LCIA or, how to avoid the Cinderella effect? International Journal of Life cycle assessment 11:219-221.

Van Dijk, A.I.J.M. and L.A. Bruijnzeel. 2001. Modelling rainfall interception by vegetation of variable density using an adapted analytical model. Part 1: Model description. Journal of Hydrology 247:230-238.

Vandenbempt P. 2008. Bio-diesel production form palm oil: life cycle and relevant impact categories. Katholieke Universiteit Leuven.

Wehrli, A., A. Zingg, H. Bugmann, and A. Huth. 2005. Using a forest patch model to predict the dynamics of stand structure in Swiss mountains forests. Forest Ecology and Management 205:149-167.

Will, R.E., N.V. Narahari, B.D. Shiver, and R.O. Teskey. 2005. Effects of planting density on canopy dynamics and stem growth for intensively managed loblolly pine stand. Forest Ecology and Management 205:29-41.