Trade-offs between land and water use: regionalized impacts of energy crops

Stephan Pfister[1,*], Michael Curran[1], Annette Koehler[1] and Stefanie Hellweg[1]

[1]ETH Zurich, Institute of Environmental Engineering, Schafmattstr. 6, 8093 Zurich, Switzerland

ABSTRACT

The environmental impact of land and water use in agriculture is highly variable on a global scale. Generally, these aspects dominate impact results of single score assessment methods such as eco-indicator 99 (EI99). Currently, no regional inventories have been provided on a global scale, and also regionalized, comprehensive impact assessment methods are lacking. We combined major land use approaches in LCA using EI99 as baseline, and applying spatially resolved factors based on ecosystem vulnerability and net primary productivity on a spatial resolution of 5 arc-minutes (<10*10km^2). Application of the resulting characterization factors in combination with water-use impact assessment reveals the global variability of regionalized inventories and impacts for crops in relation to global averages. In most cases, the impacts of land use outweigh those of water use. The results indicate locations of special environmental concern and are thus valuable to decision makers, such as producers, retailers, and consumers.

Keywords: LCIA, water use, land use, regionalization, energy crops

1. Introduction

Water and land use are key elements for environmental impact assessment of agricultural production (Köllner 2000; Pfister *et al.* 2009). In traditional LCA studies of agro-products using established methods such as Eco-indicator 99 (EI99), land use generally dominates the aggregated environmental impact (Pfister *et al.* 2009). However, recent development of LCIA methods for water use and their application have shown that water consumption is also highly relevant and may, depending on the location, even outweighs land use in importance. Spatial variability is a crucial feature in water and land use LCIA, and therefore regionalized methods are needed. While water-use impact methods are commonly regionalized, prominent methods for assessing land use are not spatially differentiated. We therefore developed geographically explicit land use impact factors. Currently, one of the mostly commonly employed methods assesses ecosystem quality through the indicator “potentially disappeared fraction of plant species” (Köllner 2000) and is implemented in the EI99 methodology ($CF_{LU,EI99}$, [PDF]) (Goedkoop *et al.* 2001). Factors are provided for different types of land use. Other methods assess biotic productivity of the ecosystem as a function of net primary productivity (NPP, [gC/(m^2*year)]) or its derivatives, and some are based on soil quality (Mila I Canals *et al.* 2007). Integration of NPP values implicitly covers additional biodiversity aspects such as vertebrate diversity or rainforest hotspots (Pfister *et al.* 2008). Other authors focused on vulnerability and scarcity of the ecosystem to improve the ecosystem quality assessment (Weidema *et al.* 2001). In spite of all these approaches, a consistent and compatible regional model for both land and water use impacts in LCA is still missing. Such a method is needed to appropriately assess and compare the environmental performance of agricultural goods.

---

* Corresponding Author. e-mail: pfister@ifu.baug.ethz.ch

2. Methods

Our regionalized LCIA approach is targeting impacts on ecosystem services and is therefore complementary to the plant species biodiversity metric. We adjusted the land use characterization factors provided in EI99 ($CF_{LU,EI99}$) based on NPP values of the potential natural vegetation ($NPP_{0,i}$) in each location (on a 5 arc-minutes resolution) and integrate regional vulnerability factors to adjust the regional impacts (ecoregion-specific). We also provide regionalized factors for the carbon sequestration potential (CSP) of land transformation and occupation (Müller-Wenk *et al.* 2010) and its climatic impact.

The final step is the combination of our LCIA scheme for land and water use with global land occupation and water consumption inventory data of the most relevant energy crops for analyzing optimization potentials and the land water trade-off.

2.1. Land use method

In order to capture the most significant impacts from land use we include land occupation, land transformation and the related impact on climate change, biodiversity and productivity of the ecosystem as depicted in Figure 1. Biodiversity is included on a local and regional level. Impacts of land use on climate change are modeled as prevented CSP and regionalized on biome level. The impacts are given as damage on ecosystems in units of PDF*m^2*year and CO_2-eq., respectively, and finally compared on the single score level of EI99. Soil-quality related impacts (Mila I Canals *et al.* 2007) are not specifically addressed here but implicitly captured by CSP and $NPP_{0,i}$ considerations.

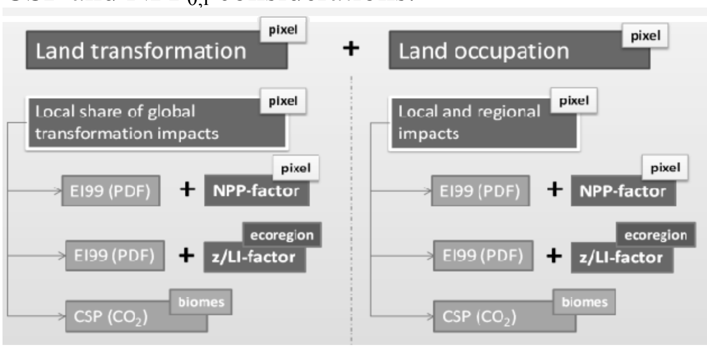

Figure 1: Regionalized impact assessment scheme for land use based on EI99, consisting of land occupation and transformation impacts. PDF is regionally adjusted by NPP_0 for each pixel (NPP-factor) and by ecosystem vulnerability (z/LI-factor) for each ecoregion. CSP factors are included on biome level.

Land occupation

The most obvious intervention of land use is occupation. For impacts on ecosystem quality, we combined the species-based and NPP approaches, using the land occupation characterization factors provided in EI99 ($CF_{LO,EI99}$) as baseline and applying spatially resolved NPP values of the potential natural vegetation ($NPP_{0,i}$) from Haberl *et al.* (2007), for deriving regionalized characterization factors of land occupation ($CF_{LO,i}$) for each location *i*. The values are normalized with the average NPP_0 of Swiss lowlands ($NPP_{0,SLL}$ = 650 gC/(m^2*year)), as the $CF_{LO,EI99}$ factors are developed for this region. Thus, the ratio of $NPP_{0,i}$ and $NPP_{0,SLL}$ functions as a weighting factor for regionalization.

$$CF_{LO,i} = CF_{LO,EI99} * NPP_{0,i} / NPP_{0,SLL} \quad (1)$$

Using NPP_0 for the spatial differentiation is an objective measure for the productivity of the land, which is crucial for life supporting functions. As productive land is limited on global scale, the most productive lands are also most attractive for human activities and should therefore also be assigned higher weights from a resource-competition perspective.

In addition to the local impact, we also developed a regional impact describing the ecosystem vulnerability (zLI_j) for each ecoregion j:

$$zLI_j = \frac{z_j}{(100-HFI_j)/100} = \frac{\gamma * \sum_k^n p_{k,j}\sigma_k}{(100-HFI_j)} * 100 \quad (2)$$

where HFI_j is the human footprint index quantifying the disturbance of natural ecosystems by humans (Sanderson *et al.* 2002), z the species-area accumulation factor, γ the standard z-factor of forest habitat (0.35), $p_{j,k}$ the area share of habitat k, and σ_k the LU change sensitivity factor of habitat k for species in the ecoregion. We differentiate two habitats per ecoregion: σ_{forest} (1.0) and $\sigma_{grass\text{-}shrub}$ (0.6). The combined local and regional characterization factors for ecosystem quality ($CF_{EQ,occupation,i,j}$) is described as follows:

$$CF_{EQ,occupation,i,j} = CF_{LO,\,EI99} * \underbrace{\frac{NPP_{0,i}}{NPP_{0,SLL}}}_{NPP-factor}\left(1 + z_{EI99}\underbrace{\frac{zLI_j}{zLI_{PA0445}}}_{z/LI-factor}\right) \quad (3)$$

where zLI_{PA0445} is zLI of ecoregion PA0445 (comprising Swiss lowlands). At_{LO} is the area-time occupied. Impacts on climate change (CSP [CO_2]) are assessed applying the occupation factors of Müller-Wenk *et al.* (2010) in the respective biomes.

Transformation

Land transformation is commonly treated as an inventory parameter (elementary flow) of processes. However, land transformation should be treated as a separate process, i.e. clearing land. Due to the lack of reliable regionalized inventory data, a factor for average transformation might be related to land occupation. The allocation of transformed land to subsequent land uses is so far not consistently included in LCA and is a question of the system boundary choice. Concerning crop production, the system boundaries should include the global agricultural system: Due to international trade and an increasing population, land transformation is inevitable to satisfy food, fibre and energy demands of humanity. This view also matches the consequential perspective which tries to assess the effect of an action on the relevant market and its consequences instead of allocating damage to different outputs of the system. Globally, fertile land is a limited resource. Hence, if global demand for agricultural goods increases, the occupation of productive land will eventually lead to transformation of natural ecosystems such as rainforests in other parts of the world - even if the studied production site is not directly implying land transformation.

The transformation of land should be attributed among agricultural production systems and other causes such as logging or peat harvesting. To take a conservative approach we attributed all damage to crop production and pastures: The amount of the annual global transformation from natural land and pastures to agricultural land is attributed to the reference agricultural area using the total land occupied by agriculture in 2007 as denominator. We used the land use changes from 1907-2007 and 1987-2007 and averaged the results to calculate annual global impacts of transformation ($IMPACT_{global,year}$) based on data from Ramankutty (2010). The transformation impact factor ($CF_{transformation,i}$) attributes the damage based on the $NPP_{0,i}$ of each pixel i:

$$CF_{transformation,\,i} = \frac{IMPACT_{Global,year}}{area_{agri.year}} * \frac{NPP_{0,i}}{NPP_{0,global}} \quad (4)$$

where $NPP_{0,global}$ is the global average NPP_0 on croplands: 611gC/(m^2*year). The currently used restoration time for ecosystem quality in EI99 of 30 years has been adapted to updated data by Schmidt (2008) for different vegetation types and adapted based on the geographical position (elevation and latitude) as suggested by Weidema *et al.* 2001.

The reference system is based on the biomes forest and grasslands, respectively, and represents the latitude and altitude of the Swiss lowlands. Grasslands have restoration times of 50 years leading to a transformation time (duration of the transformation impact) of 25 years while for forests and shrublands, the restoration time is estimated to 500 years (Schmidt 2008). We split the latter restoration time curve, based on the fact that a managed forest will be restored in 50 years and having about 80% of the original quality according to EI99. As described in Figure 2 this leads to a two-phase restoration with a relevant transformation time ($t_{transform}$) of 75 years (shaded area) for forests and shrublands.

For CO_2-emissions (CSP), we used the transformation factors of Müller-Wenk (2010).

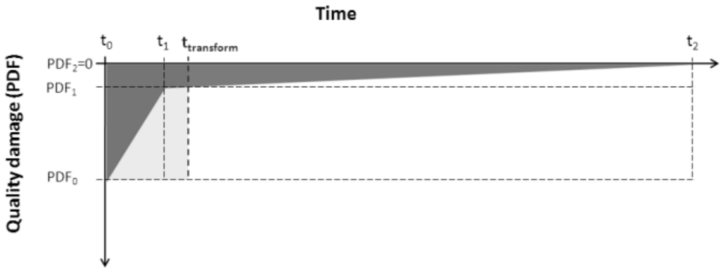

Figure 2: Two-phase restoration for forest and shrub biomes (dark area): a fast recovery of quality in the first 50 years (t_0-t_1) and a slow recovery to the original quality in the remaining 450 years (t_1-t_2). The corresponding transformation time ($t_{transform}$) is consequently 75 years (light area).

Aggregated impact (transformation + occupation)

The aggregated impacts for each pixel i are derived as follows:

$$CF_{CSP,i} = CF_{CSP,occupation,i} + CF_{CSP,transformation,i} \quad (5)$$

$$CF_{EQ,landuse,i} = CF_{EQ,occupation,i} + CF_{EQ,transformation,i} \quad (6)$$

2.2. Impact assessment of energy crops

The resulting regionalized factors require spatially differentiated inventories, as e.g. growth periods vary substantially with climate. We used inventories of important energy crops (Table 1) on a spatial resolution of 5 arc-minutes from the year 2000, provided by Pfister et al. (unpublished) for land and water use. Water impacts are assessed by the regionalized LCIA method of Pfister *et al.* (2009). National and global average impacts of each crop are derived based on the relative production in each modeled cell in order to provide the impact of the average produced product.

3. Results

3.1. Damage factors for land use

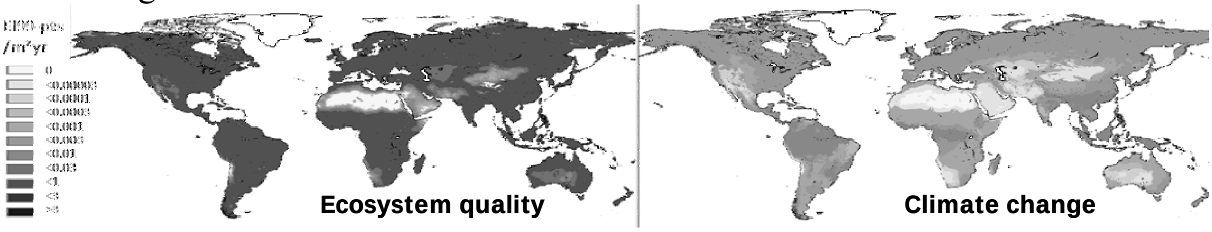

Figure 3: EI99-points per m^2year land use regarding ecosystem quality (left) and climate change change impacts on human health (right). Ecosystem quality impacts are significantly higher.

3.2. EI99-scores per kg energy crop

Land use impacts are generally higher than water use impacts (Table 1). However, regional aspects are crucial among as well as within countries as illustrated by the example of wheat in Figure 4. Spatially explicit results might therefore contradict country or global averages. Table 1 lists the global average impacts of land use and freshwater consumption for all energy crops investigated, measured as both, impacts on ecosystem quality and in EI99 aggregated single scores. Water consumption contributes significantly to the EI99-scores also through resource depletion and impacts on human health, increasing the relative relevance of freshwater consumption. Land use impacts on climate change with consequences on human health are not relevant on the EI99 single-score level. Still, land use causes higher impacts on global average than water consumption for the analyzed energy crops, except for rapeseed, soybean and sunflower.

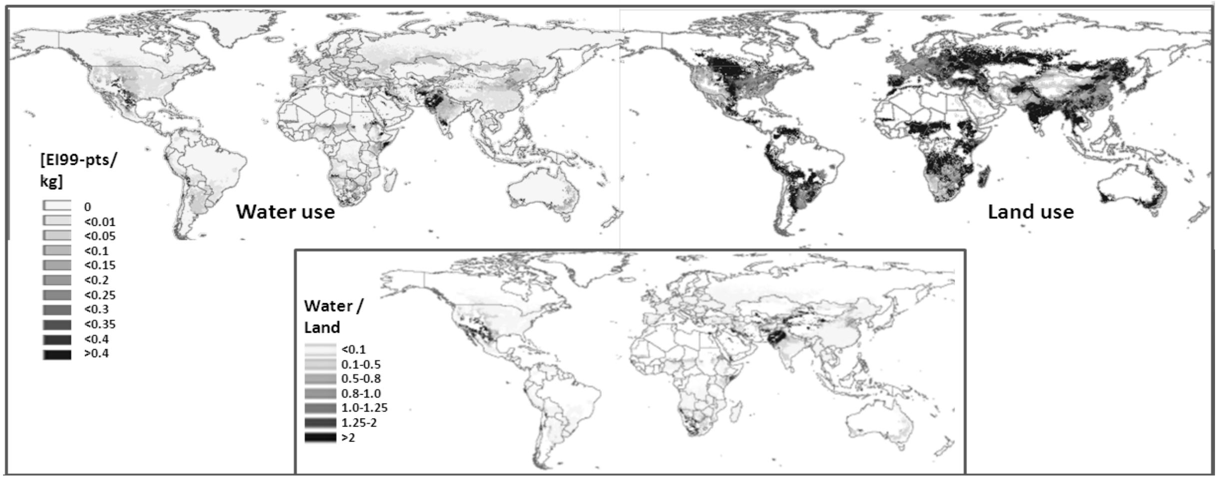

Figure 4: EI99-scores per kg wheat produced: Water use (left), land use (right). The ratio of water to land use impact is given in the bottom map indicating the relative importance of water and land in LCA of wheat.

Table 1: Global, production-weighted average impacts of land use (including transformation) and water consumption for different energy crops measured as impact on ecosystem quality and aggregated Eco-indicator 99 single-scores (EI99-pts).

	Ecosystem quality [PDF*m^2*yr/kg]			EI99-pts / kg			
	Land	**Water**	**Water/land ratio**	**Land**	**Water**	**Land+Water**	**Water/land ratio**
wheat	3.30	0.42	13%	0.26	0.07	0.33	27%
rice	2.66	0.21	8%	0.21	0.04	0.25	19%
barley	4.11	0.22	5%	0.32	0.03	0.35	9%
maize	2.00	0.18	9%	0.16	0.03	0.19	19%
rye	4.35	0.07	2%	0.34	0.01	0.35	3%
millet	10.38	0.54	5%	0.81	0.1	0.91	12%
sorghum	6.67	0.65	10%	0.52	0.08	0.60	15%
buckwheat	6.09	0.17	3%	0.48	0.04	0.52	8%
quinoa	12.46	0.1	1%	0.98	0.08	1.06	8%
potato	0.51	0.05	10%	0.04	0.01	0.05	27%
cassava	1.38	0.01	1%	0.11	0	0.11	0%
sugarcane	0.26	0.05	20%	0.02	0.01	0.03	41%
sugarbeet	0.26	0.03	12%	0.02	0.01	0.03	41%
soybean	0.37	0.21	57%	0.02	0.05	0.07	205%
oilpalm	0.17	0.02	12%	0.01	0	0.01	0%
sunflower	0.78	0.4	51%	0.06	0.08	0.14	131%
rapeseed	0.57	0.32	56%	0.05	0.08	0.13	164%

4. Discussion

Our results clearly show the importance of regionalized inventory and impacts assessment as compared to global average values generally used in LCA. While biomes and ecoregions are suitable for regional ecosystem aspects and carbon emissions for land use, only the highly regionalized data for NPP_0 allows capturing the productivity of land, which is crucial to assess the relative importance of an area regarding major ecosystem services relevant for humanity and nature. Starting from the highest available relevant spatial resolution facilitates optimization of agricultural practice by identifying hotspots of environmental concern and by identifying potential areas of relatively low environmental harm. Based on local production amounts, national or global averages can be derived and, in combination with markets and trade information, the proper production mix can be attributed to a specific regional activity.

The wheat example shows clearly the trade-off between land and water use: the least land use impact is found in areas with high water impacts such as north-west India and south-west USA (Figure 4). And although water on global average only causes a quarter of the land impact, in these regions water use is by far more damaging than land use.

Among energy crops, we found large differences. For instance, the impact scores of maize and millet differ by almost a factor 5 on global average (Table 1). In the case of millet, poor agricultural management and low yields might contribute significantly to high impacts.

Future method development should include more taxons for species diversity and further analysis of ecoregion features and vulnerability measures as well as soil-related impacts. Integration into other methods such as RECIPE or IMPACT2002 might change the results if climate change impacts on ecosystem quality are included or different weighting are applied. Furthermore, allocation of transformation damages to biomaterial harvesting needs to be examined on a regional and ecoregion scale, including driving market mechanisms.

5. References

Goedkoop M, Spriensma R. (2001): Eco-indicator 99, a damage oriented LCA impact assessment method. Methodology report Nr. 1999/36a. 3rd ed. The Netherlands, Amersfoort.

Haberl, H., *et al.* (2007). Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *PNAS* 104(31): 12942-12945.

Koellner T. (2000): Species-pool effect potentials (SPEP) as a yardstick to evaluate land-use impacts on biodiversity. *Journal of Cleaner Production* 8:293-311.

Milà i Canals L, *et al.* (2007): Key elements in a framework for land use impact assessment within LCA. *International Journal of LCA* 12(1):5-15.

Müller-Wenk, R. and M. Brandão (2010). Climatic impact of land use in LCA – carbon transfers between vegetation/soil and air. *International Journal of LCA* 15(2): 172-182.

Pfister S. *et al.* (2008): Water-use related ecosystem impacts: Comparing different indicators on global scale, http://www.lcainfo.ch/df/DF35/DF35_08_Pfister_DF35Water.pdf.

Pfister, S., Koehler, A., Hellweg, S. (2009): Assessing the environmental impacts of freshwater consumtion in LCA. *Environ Science and Technology*, 43(11): 4098–4104.

Ramankutty N. (2010): Global cropland and pasture data. McGill University.

Schmidt, J. H. (2008): Development of LCIA characterisation factors for land use impacts on biodiversity. *Journal of Cleaner Production* 16(18): 1929-1942.

Sanderson, E. W *et a.l* (2002): The human footprint and the last of the wild. Bioscience 2002, 52(10): 891-904.

Weidema BP, Lindeijer E. (2001): Physical impacts of land use in product life cycle assessment. Final report of EURENVIRON-LCAGAPS on land use. Lyngby, Denmark.