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LAND USE IN LCA

Choice of land reference situation in life cycle impact assessment

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Abstract

Purpose Land use life cycle impact assessment is calculated as a distance to target value—the target being a desirable situation defined as a reference situation in Milà i Canals et al.'s (Int J Life Cycle Assess 12(1):2–4, 2007) widely accepted framework. There are several reference situations. This work aims to demonstrate the effect of the choice of reference situation on land impact indicators.

Methods Various reference situations are reported from the perspective of the object of assessment in land in life cycle assessment (LCA) studies and the modeling choices used in life cycle land impact indicators. They are analyzed and classified according to additional LCA modeling requirements: the type of LCA approach (attributional or consequential), cultural perspectives (egalitarian, hierarchist or individualist), and temporal preference. Sets of characterization factors (CF) by impact pathway, land cover, and region are calculated for different reference situations. These sets of CFs by reference situation are all compared with a baseline set. A case study on different crop types is used to calculate impact scores from different sets of CFs and compare them.

Results and discussion Comparing the rankings of the CFs from two different sets present inversions from 5% to 35% worldwide. Impact scores of the case study present inversions of 10% worldwide. These inversions demonstrate that the choice of a reference situation may reverse the LCA conclusions for the land use impact category. Moreover, these reference situations must be consistent with the different modeling requirements of an LCA study (approach, cultural perspective, and time preference), as defined in the goal and scope.

Conclusions A decision tree is proposed to guide the selection of a consistent and suitable choice of reference situation when setting other LCA modeling requirements.

1 Introduction

Land use impacts several natural cycles, including the carbon and water cycles. The Food and Agriculture Organization (FAO) drew attention to this underestimated issue by designating 2015 as the International Year of Soils. In life cycle assessment (LCA), the impact assessment of land use relies on the widely accepted (Klöppfler and Grahl 2014; Mattila et al. 2011) framework set out by Milà i Canals et al. (2007), as per Eq. (1):

$$\text{Impact score} = A \cdot t \cdot CF, \text{ with } CF = \Delta Q = Q_{\text{reference}} - Q_{\text{land use}}$$

(1)

where A is the surface of used land (m^2), t the land use duration (years), CF the characterization factor (CF), and Q the soil quality (physical unit of the impact pathway assessed).

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The *surface x time* factor and characterization factor (CF) respectively embed the *extensive* and *intensive* characters of the land activity. The CF is calculated with respect to a reference (a modeling choice) that is in line with a *distance to target* metric: the closer to the target (intended as a desired state), the lower the impact. In Milà i Canals et al. (2007), the impact calculation is computed as a difference from a reference through a baseline $Q_{reference}$, referring to non-use of the land.

The baseline set out in the Milà i Canals et al. (2007) framework has been interpreted quite literally in the life cycle impact assessment community to refer to undisturbed land or land without human presence. Although these two baselines may appear close to each other, they fundamentally differ in fact: the first refers to a pristine land state (which has existed in the past or would be achieved without human presence) while the second acknowledges the human use of land and refers to the state of the land after use and a sufficient relaxation period. The latter is the recommended baseline (Milà i Canals et al. 2007; Koellner et al. 2013; EU Joint Research Center 2010; Soimakallio et al. 2015), although this is inconsistent with other guidelines (BSI 2011; WRI and WBCSD 2011) and the state of practice: in the review of Soimakallio et al. (2015), 80% of the studies analyzed are without explicit baseline.

Numerous subtle differences exist when translating the baseline into reference situations (Electronic supplementary material, Sect. 1). Different visions exist. The land without human presence is mainly modeled by the potential natural vegetation (PNV), which is the dynamic equilibrium reached under current climatic conditions (Levavasseur et al. 2013). PNVs are derived from sophisticated environmental models known as dynamic general vegetation models (Cramer et al. 2001) such as BIOME3 (Haxeltine and Prentice 1996), which simulate the climate based on given environmental parameters. PNV is relative to a prospective theoretical future but is not a prediction (Loidi et al. 2012). The PNV concept, while often cited as the recommended reference situation in LCIA, is challenged by other branches of the natural sciences, such as nature conservation, ecology, and evolutionary biology (Chiarucci et al. 2010). The concept is static, deterministic and rely on highly uncertain climatic predictions. It does not include existence of random biological processes and vegetation dynamics, which are complex to model (Chiarucci et al. 2010).

Few model developers have discussed their choice of reference situation. The hemeroby concept is a measure of naturalness and is exclusive to a reference situation relative to a natural or quasi-natural state (Brentrup et al. 2002). Schmidinger and Stehfest (2012) performed CO_2 calculations for livestock relative to a specific baseline representing a reduced production scenario but discussed other possibilities: historic land use change, transformation, and delayed

restoration and continued current state, which are similar to the three first reported by Soimakallio et al. (2015). De Baan et al. (2013) calculated terrestrial biodiversity CFs relative to natural regeneration and discussed retrospective and prospective reference situations (i.e., CF assessing impacts due to past land use versus impacts that would cause marginal impacts due to additional land use). In the context of terrestrial biodiversity, de Souza et al. (2015) pointed out how difficult it is to determine a reference situation. Michelsen et al. (2015) added that the consequences of selecting different reference states (for biodiversity impact assessment) are not understood well enough and should become a priority area for further research.

The selection of the reference situation in land use impact characterization should be consistent with the LCA's goal and scope (Milà i Canals et al. 2007). This first step defines the purpose of the LCA. Because of the comparative character of LCA, the choice of the reference situation affects the comparison of different systems and the relevance of this modeling choice has received little attention until recently. Soimakallio et al. (2015) demonstrated the need for a baseline in attributional LCA (not specifically to land use). The authors performed a meta-analysis of approximately 700 LCA studies and by reviewing their goal and scopes, they identified four main visions to support the baseline choice in LCA: (1) natural or quasi-natural steady state, (2) natural regeneration, (3) business-as-usual, and (4) zero baseline. Natural or quasi-natural steady state refers to a state with no human influence. Natural regeneration describes the natural state achievable after human land use has ceased (after relaxation). Business-as-usual assumes that future land use is known, based on current use, and with no further human intervention. Zero baseline is explicit and equivalent to accounting observable impacts only. This baseline is appropriate to describe land in a natural state when land use begins.

From both the goal and scope and the vision set, different LCA modeling requirements are derived: the LCA approach (attributional or consequential), the cultural perspective (egalitarian, hierarchist, or individualist), temporal boundaries (e.g., accounting or not for long-term impacts), and the reference situation. The purpose of an attributional LCA (aLCA) is to study the impacts of a given activity relative to a situation in which it is not undertaken (Tillman 2000). Consequential LCA (cLCA) studies marginally changes so that the most probable alternate land use becomes the reference. A temporal preference may also be set through a so-called cultural perspective described by Hofstetter et al. (2000). These perspectives are mostly known and used to weigh the importance of different damage categories. However, they were originally designed to include a vision of what is to be assessed in the LCA and all the subjective choices of an LCA model, including how the natural environment, the time, or the scientific criteria (e.g., evidence or experience) are perceived (cf. Electronic supplementary material, Sect. 2). Given that the

basic purpose of LCA is to catch all impacts in time or space based on the goal and scope (Hauschild et al. 2013), the reference situation and the other LCA modeling choices all relate to the vision defined and they should be consistent. However, Soimakallio et al. (2015) found out that this is clearly not the case in actual state of practice.

Given the lack of consistency between the choice of reference situation when assessing the potential impacts of land use with the vision defined in the goal and scope of an LCA, the following objectives are set out: (1) describe the differences in land reference situations and discuss their relationship to life cycle impact characterization modeling requirements, (2) illustrate the influence of the choice of reference situation on CFs and impact scores through a case study, and (3) provide a decision tree to guide the choice of reference situation consistent with the goal and scope of an LCA.

2 Methods

2.1 Land reference situations: description and classification

2.1.1 Description of reference situations

The reference situation is defined as a desired land state. Such states may be the natural steady state, the regeneration state, or the permanent impacts (Milà i Canals et al. 2007). Impacts of interest may also be relative to the visions reported by Soimakallio et al. (2015), adding the business-as-usual and baseline 0 reference situations. Finally, land quality is also commonly compared with thresholds defined by regulations or natural boundaries (Newbold et al. 2016). The different reference situations can be summarized as per Fig. 1.

In Fig. 1, the y-axis presents different land qualities:

Q_A Quality before land use (occupation and transformation), natural at steady state
Q_B Quality after transformation and at the beginning of the occupation t_B
Q_C Quality at the end of the occupation t_C
Q_D Quality after natural relaxation from anthropogenic use, at t_D
Q_T Threshold quality, defined by regulation or based on scientific information

In aLCA, the CF is calculated as the land quality loss relative to a reference situation (Milà i Canals et al. 2007) and defined as Eq. (2a):

$$CF_{\text{land use}}^{\text{attributional}} = Q_{\text{reference}} - Q_{\text{land use}} \qquad (2a)$$

A common simplification is to consider $Q_C \approx Q_B$ (i.e., the occupation impacts being much in cLCA, marginal changes

based on a decision from a given situation are studied (Milà i Canals et al. 2007). The reference situation term is therefore absent (Eq. 2b).

$$CF_{\text{land use}}^{\text{consequential}} = Q_{\text{alternate land use}} - Q_{\text{land use}} \qquad (2b)$$

Different reference situations are described for aLCA CF calculations in the following equations. Natural steady state is the original situation *without* land use (natural or quasi-natural steady state vision) and regeneration state comes after natural relaxation from land use (natural regeneration vision). Both result from modeling and therefore involve uncertainty (Levavasseur et al. 2013). They are taken from Milà i Canals et al. (2007) and defined as:

$$\Delta Q_{\text{natural steady state}} = Q_A - Q_B \qquad (3)$$

$$\Delta Q_{\text{regeneration state}} = Q_D - Q_B \qquad (4)$$

Permanent impacts are calculated as the difference between them:

$$\Delta Q_{\text{permanent impact}} = Q_A - Q_D \qquad (5)$$

This reference situation is particular and different to the others to the extent that it does not describe actual and temporary impacts of the occupation and regeneration phases.

The threshold state refers to an acceptable land situation, whether set out by regulation or the scientific community, through concepts such as a planetary boundary or a safe operating space (Rockström et al. 2009; Steffen et al. 2015):

$$\Delta Q_{\text{threshold}} = Q_B - Q_T \qquad (6)$$

For instance, tolerable erosion rates (European Environment Agency 2006; Organization for Organisation for Economic Co-operation and Development (OECD) 2001) or groundwater safe yield (Alley and Leake 2004) are possible concepts.

Business-as-usual and baseline 0 were reported based on the goal and scopes review by Soimakallio et al. (2015). Business-as-usual considers the ongoing human activities without further land changes brought by humans:

$$\Delta Q_{\text{business-as-usual}} = Q_{B'} - Q_B \qquad (7)$$

Baseline 0 considers no impacts at the start of occupation (observable impacts) and should be used to assess human activities occurring on land in its natural state:

$$\Delta Q_{\text{baseline 0}} = Q_B - 0 = Q_B \qquad (8)$$

The quality losses according to the different reference situations are reported as double arrows on the right side of Fig. 1. Considering the quality of alternate land use $Q_{B'}$ close to Q_C, business-as-usual is represented as equal to $Q_B - Q_C$ to simplify Fig. 1.
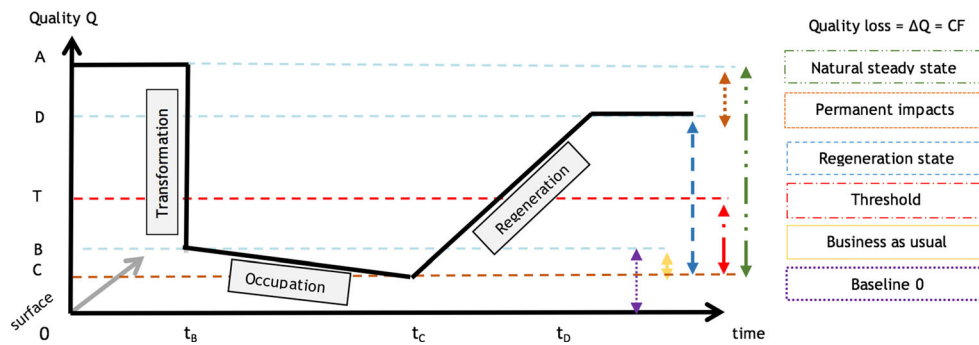
Fig. 1 Reference situations (*colored rectangles on the right-hand side*) and their related characterization factor (*CF*) representation within the land use impact assessment framework by Milà i Canals et al. (2007). A CF represents the quality loss with respect to a given reference situation, as reported by the *double arrows on the right side of the figure*

2.1.2 Classification of reference situations

Based on the descriptions of each vision (Soimakallio et al. 2015) and the definitions of the attributional and consequential LCA approaches, the reference situations described in Sect. 2.1.1 section were analyzed according to cultural perspectives (Hofstetter et al. 2000) (Electronic supplementary material, Sect. 2) and temporal preference.

2.2 Effect of the reference situation on land use characterization

2.2.1 Effect on characterization factors

In this work, a set of CFs is defined for x different land uses in y different regions. One set is composed of $x \cdot y$ values and calculated for a given reference situation, as per Eqs. (3) to (7). The $x \cdot y$ values of each set are compared with the values from the baseline 0 reference situation set (Eq. 8). The percentage of ranking differences with the baseline 0 set is reported as an inversion between the set and the baseline 0 set. The effect of the reference situation on land use characterization factors $CF^y_{land\ use}$ are analyzed by (1) setting regions y and reporting inversions of rankings on land use types x and (2) setting land use types x and reporting inversions of rankings through the y regions. To ensure robustness, the inversions are reported for several value gaps between the sets from the different reference situations.

CFs are usually published as single values, whereas the methodology used here requires access to the two members $Q_{land\ use}$ and $Q_{reference}$ of Eq. (2a). We therefore based our analysis on values from Saad et al. (2013), which provide both land use quality members for the CF calculation. Erosion resistance potential, freshwater recharge potential, and mechanical and physicochemical water purification potential CFs were developed for eight main land cover classes (artificial green urban, fallow grounds, forest,

grassland, pastures, permanent and annual crops, shrubland, and urban) and differentiated for 36 biogeographic units, the Holdridge lifezones ($x = 8$ and $y = 36$). In each lifezone, one land cover class was identified as the reference situation. The geographic information system (GIS) was used for the calculations. The reference situation adopted by Saad et al. (2013) is based on PNV, which may be different from one modeling to the next since it evolves according to current conditions. The authors used the PNV map from Ramankutty and Foley (1999), where PNVs were derived from the dynamic general vegetation model BIOME3 (Haxeltine and Prentice 1996). This reference situation is referred to as PNV R99. Levavasseur et al. (2013) compared different dynamic general vegetation models: BIOME3 (Haxeltine and Prentice 1996), BIOME4 (Kaplan et al. 2003), and BIOME6000 (Harrison et al. 2003). They derived maps of dominant PNVs and next-to-dominant PNVs with their respective probabilities of occurrence. We determined a reference situation as the weighted sum of the dominant and next-to-dominant PNVs for all the Holdridge lifezones and this reference situation is referred to as PNV L13.

CFs are calculated for the baseline 0, PNV R99, and PNV L13 reference situations. Since there is no consensus on water purification thresholds, the reference situation was not tested. The natural steady state was not modeled since it relies on a temporal choice (how much time back to model) and modeling Q_A requires the use of sophisticated dynamic general vegetation models. The permanent impacts reference situation was also left out since it also requires the definition of temporal boundaries. No definition would lead to calculating infinite impacts, given the land duration parameter $t = t_D − t_A$ (cf. in Eq. 1) associated with this reference situation.

2.2.2 Effects on impact scores

A similar approach is applied to evaluate the effect of the reference situation on LCA impact scores comparing results

from a case study on bio-based polymers. The functional unit (FU) is defined as producing a fork from bio-based polymer, soybean, or wheat. Two types of crop land covers are compared on common feedstock locations worldwide: 4025 cells located in 54 different countries in the MIRCA2000 database (Portmann et al. 2010). In this case, $x = 2$ and $y = 4025$.

The inventory values are based on data from Table 1. Land use inventory values (m²·year/FU, from Eq. 2a) are calculated as the product of crop yield, polymer content by crop, and polymer input per fork. Input data for each parameter are reported in Table 1, along with the range of crop yield by country calculated as annual 2009–2013 average (FAOSTAT 2015) (detailed information by country is given in the Electronic supplementary material, Sect. 3).

Because multiplying CFs from Sect. 2.2.1 with inventory values would only show the effect of these inventory values on the CFs, different CFs from the ones used in Sect. 2.2.1 were tested to show the effect of the reference situation choice on the impact scores. Erosion and runoff CFs were calculated with the Water Erosion Prediction Project (WEPP) model and parameterized with MIRCA2000 (Portmann et al. 2010) data. The CFs of wheat and soybean land covers were compared on all common cultivation places (4025 grid cells –0.5° by 0.5°, worldwide) and tested for baseline 0, business-as-usual, PNV R99, PNV L13, and threshold reference situations. In this work, the business-as-usual scenario considered ongoing activities so that $Q_{B'}$ is equal to Q_B (i.e., $\Delta Q_{\text{business-as-usual}} = 0$). The erosion threshold value is based on the tolerable erosion rate value of 1 t/(ha·year) released by the European Environment Agency (1998), and the runoff value of 10 mm/year is based on the minimum of world groundwater recharge per country, excluding arid countries (i.e., 5th percentile) (Döll and Fiedler 2008).

2.3 Guidance for selecting reference situations according to LCA modeling requirements

The choice of the reference situation must be consistent with the LCA modeling requirements defined by the goal and scope. Three of these requirements are used as criteria to guide the choice of reference situations: (1) attributional and consequential LCA approaches, (2) LCA cultural perspectives (egalitarian, hierarchist, and individualist) and (3) temporal preference (past, present, or future). A decision tree based on these successive criteria was set out to guide the selection.

3 Results

3.1 Classification of reference situations

Table 2 presents the different reference situations in relation to other LCA modelling requirements defined in the goal and scope. Each land use reference situation (column 1) leads to a specific CF (column 3) and land occupation impact score (column 4). With the exception of alternate land use, all can be used in aLCA. Both baseline 0 and business-as-usual do not account for past conditions and suggest continuity with current land situations, corresponding to the individualist perspective and the temporal preference of present. Natural steady state should be used in an LCA study with protection purposes (conservation with reference to the past or restoration in the future) and falls in the egalitarian perspective. Because it accounts for impacts from current land use to a distant future, permanent impacts also belong in this perspective. The egalitarian perspective is the closest to Hauschild et al.'s (2013) definition of LCA catching all impacts through time and space. The regeneration state refers to a future that acknowledges current conditions and suits an in-between perspective: the hierarchist position. A threshold reference

Table 1 Inventory data for the production of bio-based polymers for the fork production case study

Product system	Polyhydroxyalkanoate (PHA) soybean	Thermoplastic starch (TPS) wheat
Polymer input[a] (g$_{\text{polymer}}$/FU)	3.29	3.29
Crop content (g$_{\text{crop}}$/g$_{\text{polymer}}$)	7.31[b]	1.67[c]
Crop input (g$_{\text{crop}}$/FU)	24.08	5.49
Yield (min-max across the world) [g$_{\text{crop}}$/(m²·year)]	$3.12 \cdot 10^1 - 2.86 \cdot 10^2$	$2.18 \cdot 10^1 - 2.99 \cdot 10^3$
Median	$1.86 \cdot 10^2$	$4.76 \cdot 10^2$
Land use inventory, min-max across the world [(m²·year)/FU]	$8.43 \cdot 10^{-2} - 7.72 \cdot 10^{-1}$	$1.83 \cdot 10^{-3} - 2.52 \cdot 10^{-1}$
Median	$1.29 \cdot 10^{-1}$	$1.15 \cdot 10^{-2}$

Input = starch from maize and wheat for TPS systems and soybean oil for PHA soybean; values are rounded

FU stands for functional unit; yield varies based on country

[a]: Fork volume-constrained calculation with polymer densities; [b]: Kahar et al. 2005; [c]: Shen, Haufe & Patel 2009

Table 2 Reference situation with corresponding characterization factors and relationship to life cycle assessment (LCA) modelling requirements

	Land reference situations and corresponding characterization factors (CF)				LCA modelling requirements		
Reference situation	Land quality	$CF_{land\ use}$	Impact of land occupation (Illustrated considering $Q_B = Q_C$)	Land transformation	Approach	Cultural perspective	Temporal preference
Baseline 0	$Q_{reference} = 0$	Q_B		From 0 to Q_B	Attributional	Individualist	Present
Business as usual	$Q_{reference} = Q_{B'}$	$Q_{B'} - Q_B$		None: land activity continues without *further* intervention	Attributional*	Individualist	Present
Natural steady state	$Q_{reference} = Q_A$	$Q_A - Q_B$		From Q_A to Q_B	Attributional*	Egalitarian	Past or future, *without humans*
Permanent impacts	$Q_{land\ use} = Q_D$ $Q_{reference} = Q_A$	$Q_A - Q_D$		From Q_A to Q_D	Attributional	Egalitarian	Present Future
Regeneration state	$Q_{reference} = Q_D$	$Q_D - Q_B$		From Q_D to Q_B	Attributional*	Egalitarian / Hierarchist	Future
Threshold	$Q_{reference} = Q_T$	$Q_B - Q_T$ (algebric value)		-	Attributional*	Depends on the threshold severity	Present
Alternate land use	$Q_{reference} = Q_{B''}$	$Q_{B''} - Q_B$	-	From Q_B to most probable alternate land use	Consequential	Hierarchist	Present Future

Notes: 1) Land occupation and land transformation refer to LCA elementary fluxes for land use and land use change induced by humans. 2) Business-as-usual land use without further human intervention ($Q_{B'}$) and most probable alternate land use, natural or not ($Q_{B''}$) are to be defined in goal and scope. 3) In the indicative figures, the third axis is the surface of the land use (see Fig. 1). 4) Attributional* means that the reference situation may be used as the alternate land use required in consequential LCA.

situation based on regulation represents a realistic compromise between protection and affordability and would be close to a hierarchist perspective. Upon the recommendation of the scientific community and given the current land situation (FAO and ITPS 2015), such threshold reference situations could reflect conservation purposes and therefore be close to the egalitarian perspective. cLCA assess changes in land and refers to alternate situations to be determined according to the goal and scope of the study.

3.2 Effect of reference situation on characterization factors and impact scores

Figures 2 and 3 report the percentage of inversions in $CF_{land\ use}$ rankings for two regeneration state reference situations: PNV R99 and PNV L13. The $CF_{land\ use}$ rankings are analyzed relative to the baseline 0 reference situation for the erosion resistance (ERP), freshwater recharge (FWRP), and mechanical (WPP-MF) and physicochemical water purification
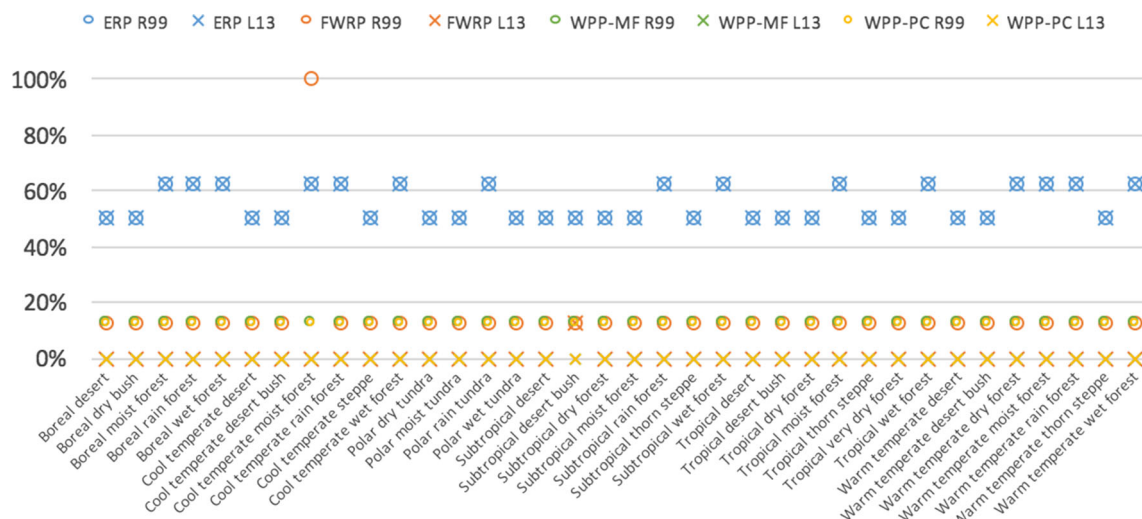
Fig. 2 Percentage of inversions in the ranking of the erosion (*ERP*), freshwater recharge (*FWRP*), and mechanical (*WPP-MF*) and physicochemical filtration (*WPP-PC*) characterization factors from Saad et al. (2013) calculated for eight land use types according to PNV L13 and PNV R99 reference situations, as compared with the baseline 0 reference situation. Results are calculated for each of the 36 Holdridge lifezones
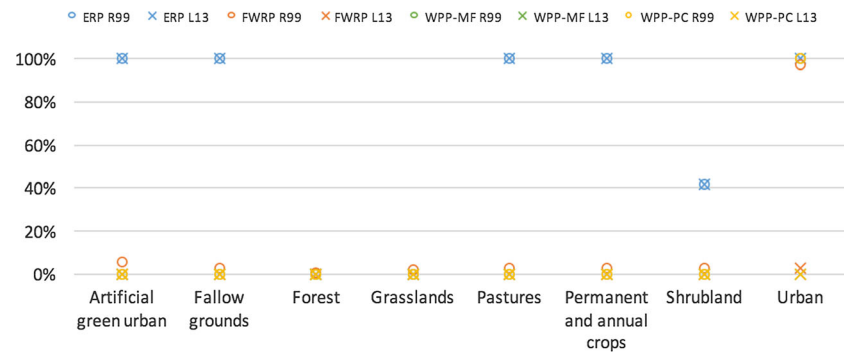
Fig. 3 Percentage of inversions of erosion (*ERP*), freshwater recharge (*FWRP*), and mechanical (*WPP-MF*) and physicochemical filtration (*WPP-PC*) characterization factors from Saad et al. (2013) describing 36 region rankings according to PNV L13 and PNV R99 reference situations, as compared with the baseline 0 reference situation by main land use types

(WPP-PC) potential impact pathways developed by Saad et al. (2013).

Inversions are observed for ERP in all Holdridge lifezones (Fig. 2). The land use types causing $CF_{land\ use}$ inversions between baseline 0 and PNV are the most anthropogenic of the eight types (the remaining forest and grassland land cover types are closer to the PNV) and therefore have more impacts than if they were assessed with baseline 0, which is equivalent to only account for observable impacts. For FWRP, WPP-MF, and WPP-PC land use characterization factors, using PNV L13 leads to no inversion of the land use types (correlated through all life zones) as compared with baseline 0, while PNV R99 leads to 26% inversion in the urban land use class. This shows that different modeling of the PNV can lead to different results. The results for different cutoff values when accepting an inversion in $CF_{land\ use}$ ranking are set out in the Electronic supporting material, Sect. 4.

The choice of reference situation PNV L13 or PNV R99 as compared with baseline 0 also leads to inversions in $CF_{land\ use}$ rankings across the 36 Holdridge lifezones for each land use type.

The ERP results from PNV L13 and PNV R99 for artificial, fallow grounds, pastures, and permanent and annual crops contrast with those from baseline 0. There are no inversions for the forest and grassland land use types. The other impact pathways do not present inversions as compared with baseline 0 through the life zones, except for the urban land use between PNV R99 and baseline 0. Figures 2 and 3 indicate that the inversion percentage affects each impact pathway differently. The two natural regeneration PNV L13 and PNV R99 reference situations also appear consistent in terms of inversions as compared with the baseline 0.

Figure 4 presents the inversions of the soybean and wheat rankings (CFs in bars, impact scores with crosses) calculated based on the PNV R99, PNV L13, threshold, and business-as-usual reference situations, as compared with baseline 0, reprising the color code in Fig. 1. The percentage of inversion in $CF_{land\ use}$ and impact score for 4025 grid cells which are common cultivation locations worldwide on the *y*-axis

indicates the share of locations where soybean and wheat values for a given reference situation rank differently from baseline 0. The *x*-axis is the minimal difference between the soybean and wheat values (CF and impact scores) considered to report an inversion.

Regardless of the difference in $CF_{land\ use}$, the baseline 0 and threshold references situations lead to similar results (no inversions). This was expected since baseline 0 CFs are calculated as $Q_{occupation}$ and threshold is equivalent to offsetting $Q_{occupation}$ with a constant throughout all locations. Compared with baseline 0, business-as-usual, and PNV L13 inversion numbers are close, slightly higher than the PNV R99 results and different from baseline 0 with inversions from 15% to 35% for a difference in CF values of less than 10 units. In other words, at least one third of the locations worldwide would have reversed conclusions for the baseline 0 reference situation and the others. The results for comparison with reference situations other than baseline 0 and runoff CFs are available in the Electronic supporting material (Sects. 4 and 5). The inversion number decreases as the difference between CFs increases.

The land use impact scores represented by crosses in Fig. 4 are the product of $CF_{land\ use}$ and life cycle inventory values. In 30% to 50% of locations worldwide, conclusions differ between the baseline 0 and PNV R99, PNV L13, and business-as-usual reference situations for a difference in impact scores of up to 10 units (on the *x*-axis). The percentage range then drops between 20% and 30%. For impact scores with large differences (>100 units on the *x*-axis), over 15% of grid cells worldwide still present ranking inversions between baseline 0 and PNV L13, PNV R99, and business-as-usual. When the system product falls in these grid cells, the choice of reference situation leads to different conclusions. Threshold presents very low inversion percentages as compared with baseline 0 since both reference situations lead to the same conclusions.

These results show that the choice of reference situation affects the $CF_{land\ use}$ and impact scores calculated from it, which may lead to inversions in LCA

Fig. 4 Percentage of inversions of wheat and soybean erosion CF (*bars*) and impact score (*crosses*) rankings for the PNV L13 (*light blue*), PNV R99 (*dark blue*), threshold (*red*), and business-as-usual (*yellow*) reference situations, as compared with baseline 0. The *x*-axis is in log-scale and constitutes the minimal difference in CF or impact score value to account for an inversion
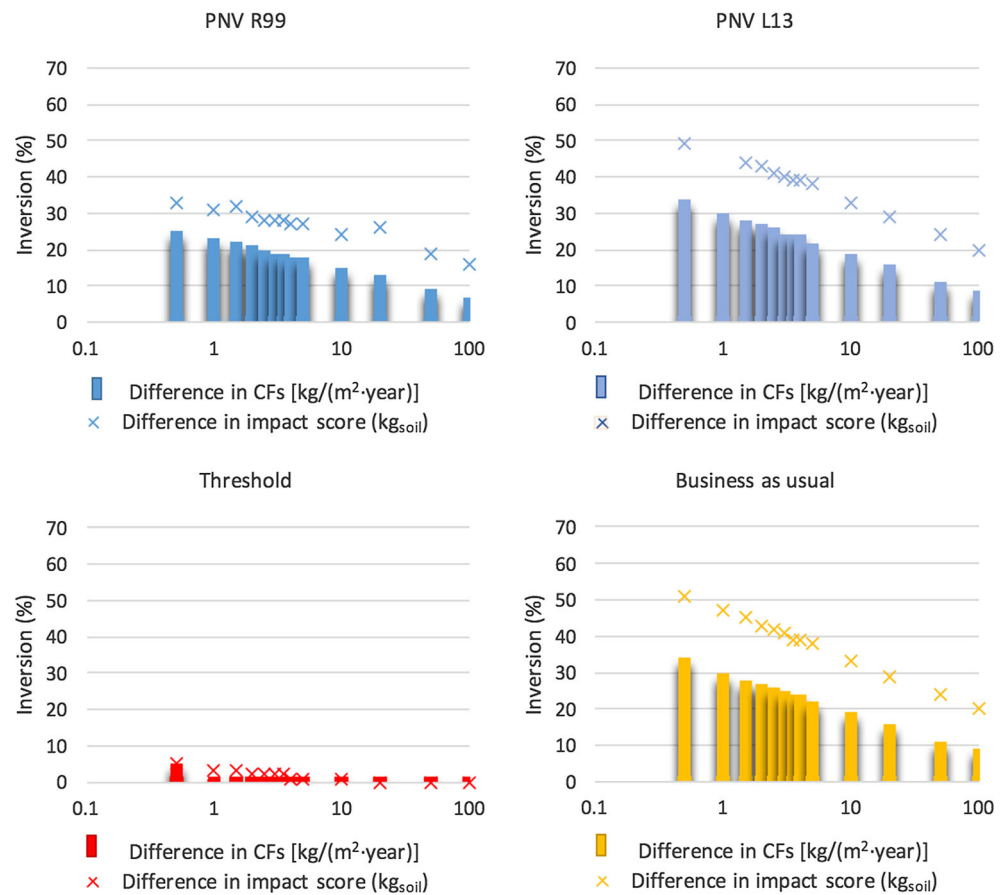
conclusions. In addition, the results from the five reference situations tested for erosion and runoff CFs are all different.

### 3.3 Guidance for selecting reference situations according to LCA modeling requirements

Table 2 presents the visions and corresponding reference situations in relation to three LCA modeling requirements. Because all four modeling elements should be consistent, LCA modeling requirements also define a vision that may be used as successive criteria to determine a reference situation. Temporal preference is more detailed than past, present, or future. A decision tree is set out in Fig. 5.

In an aLCA approach, land use impacts are assessed in relationship to a baseline. The cultural perspective and the temporal preference described in Table 2 narrow down the reference situation. Together, these four modeling elements define a consistent set to model and describe land impacts for a given vision. In the individualist perspective, short term dominates the long term and the reference situations are related to present land use. Assessing absolute and observable impacts leads to choose the baseline 0 option, which suits the situation where the land use succeeds a

natural land cover. The business-as-usual option offers a baseline where the actual activity on the land is continued. This option is suitable to capture effects of a non-continued land use, e.g., when a land activity changes. In the egalitarian perspective, the natural environment is fragile and must be protected for the future generations. Assessing impacts relative to a conservative reference would lead to prefer the natural steady state option, which accounts for the most original state of the land, in the past and before human presence. Accounting for impacts occurring in present and persisting into the future leads to the permanent impact option. In the hierachist perspective, the vision is balanced between the two others. Threshold levels have a protective purpose but originate from legislation far from maintaining soils to historical states or protecting them sufficiently (FAO and ITPS 2015). The natural regeneration reference situation also belongs to this perspective, as it acknowledges that present conditions shape the future land state, which cannot recover to its original natural steady state.

In an cLCA approach, changes in land use are assessed and require an alternate land use as the reference situation. The most probable alternate land use is suggested by Milà i Canals et al. (2013). When a human activity follows another, the reference situation would then be represented by a natural
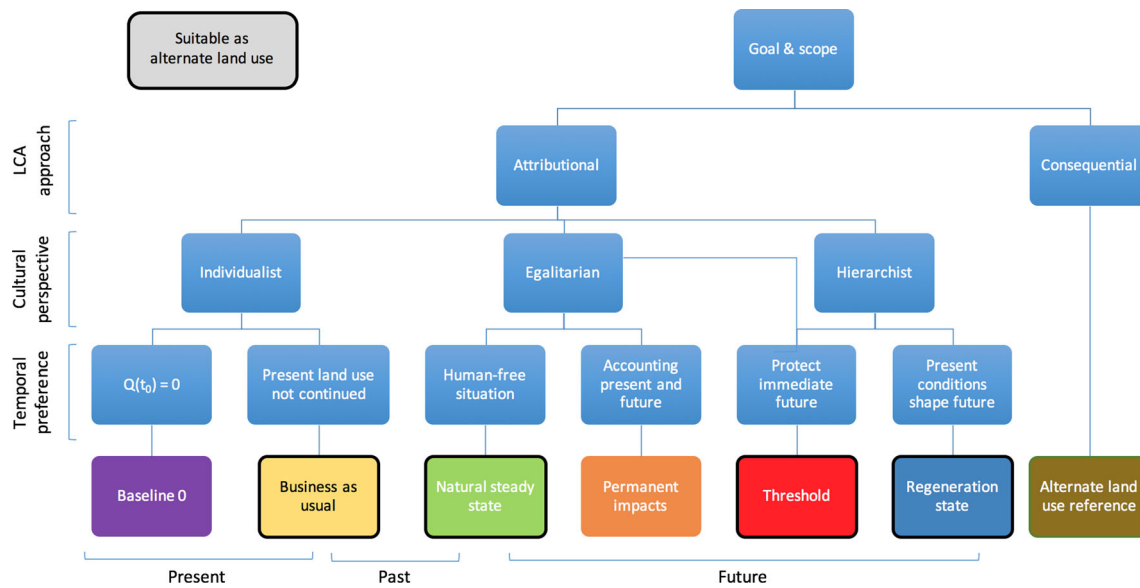
Fig. 5 Decision-tree guiding the selection of the reference situation according to three LCA modeling requirements: attributional vs. consequential approach, cultural perspective and temporal preference

land cover (not involving land use induced by humans) and certain reference situations presented for aLCA may serve as the alternate reference situation. Baseline 0 and permanent impacts are ruled out since they suggest continuity with current land occupation (no changes occur).

4 Discussion

4.1 Reference situation classification

Different reference situations were compared and categorized. We presented here a classification, but additional considerations could have been added in their description, such as the dependence of $Q_{reference}$ on $Q_{land\ use}$ or dynamic vs. static modeling. Contrary to the baseline 0 and natural steady state, the determination of the business-as-usual, natural regeneration, permanent impacts and, potentially, threshold (e.g., regulation differentiation according to land use type) reference situations is dependent on current land use. By accounting for human activity, the situations may be considered more in line with the dynamic nature of land described by Milà i Canals et al. (2007). Dynamic or static modeling may also become another criterion in the decision-tree. Currently, only impacts from an initial to a final state are assessed, regardless of the intermediary states (Othoniel et al. 2016). The uncertainty of the reference situation modeling, its discrimination power and data availability may also be selected through a practical decision tree. However, we believe that the decision tree presented in Fig. 5 and based on description of Table 1 is key to ensuring a consistent LCA modeling, since the

interpretation of the land impact scores should first be clear to the LCA practitioner (to know what to calculate) and the study's target audience.

4.2 Effect of reference situations choice on LCA calculations

The choice of the reference situation affects land use indicators differently according to the impact pathway (Figs. 2, 3, and 4), spatial differentiation (Fig. 2), and land use types (Fig. 3). Inversions in land use characterization factors and impact scores due to the choice of reference situation are far from negligible throughout all locations worldwide. This potential change in impact score ranking constitutes an additional incentive to assess land use at a given location when the information is known. In the case location is unknown or the land cover not well described (e.g., the set of CF reducing towards one generic CF), selecting a reference situation adequate to the LCA goal and scope and vision set and consistent throughout the whole LCA modeling still applies. In such case, the spatial uncertainty is high and the reference situation choice becomes all the more important. The likelihood of ranking inversions can also be interpreted as uncertainty related to either the choice of the reference situation or its modeling. As a quantitative discrimination criterion of two reference situations, the minimal differences between CF/impact scores to report an inversion (x-axis of Fig. 4) quantify this uncertainty, which can then be put in perspective with other potential sources of land impact modeling uncertainty (e.g. spatial variability).

4.3 Reference situation relationships

The results were reported in this work as compared with the baseline 0 reference situation. The comparison of the different reference situations leads to different trends between the reference situations and impact pathways and no clear relationships can be established between the different reference situations (Electronic supplementary material, Sects. 3 and 4). ERP from Saad et al. (2013) calculated with either PNV L13 or PNV R99 led to perfect consistency and no inversions from erosion CFs calculation with the WEPP model. Further work is required in that area. The relationships between the reference situations are also dependent on the spatial scale of the assessment. For instance, the spatial extent of the business-as-usual situation is the own extent of the land use, the threshold extent depends on the regulation zoning while the spatial extent of the the natural steady state or the regeneration state are of the biogeographic spatial units such ecoregions or biomes.

Natural steady state and permanent impacts were not quantified in this work. However, CF values calculated from natural steady state can likely always be considered higher than natural regeneration CF values, based on Fig. 1. The permanent impacts reference situation requires a temporal boundary to prevent integrating time duration to infinite. On the subject, permanent impacts are usually calculated separately from occupation and transformation impacts and represent long-term impacts exceeding common LCA modeling horizons (Koellner and Geyer 2013). Including permanent impacts along with the occupation or transformation impacts is equivalent to aggregate different time horizons, which requires an explicit temporal value choice. The regeneration reference situation can be used for land occupation or transformation assessment. The natural steady state fits more the land transformation impacts by definition (cf. Q_A and Q_B definitions) while the business-as-usual, the baseline 0, and the threshold reference situations are more suitable to assess land occupation, as they relate the land use assessed to immediate other possible land uses. Assessing occupation or transformation impacts with its reference situation choice is highly dependent on what is to be assess in the study, i.e., its goal and scope.

4.4 Recommendations

Whether conclusions are inverted or not, the reference situation must reflect the goal and scope and should be explicit and consistent with other LCA modeling requirements such as the LCA approach type, the cultural perspective and the temporal preference. To ensure the proper assessment and interpretation of land impact results, we recommend that LCA practitioners examine how the reference situation is modeled and refrain from using CFs that do not account for this information. LCA results for land use would be more transparent and less often taken out of the context for which they were calculated. For

instance, whether PNV should be used in aLCA is still highly debated (Brander 2015, 2016; Soimakallio et al. 2016). In the case of multiple land use indicators, consistency and ease of interpretation require that they derive from the same reference situation. As required by the fourth step under ISO14040, interpretation should be permanent and the dialog among all the LCA steps should concur with a homogeneous study.

Because the Milà i Canals et al. (2007) framework requires a reference situation, it introduces a modeling choice that should not be buried in the calculations. CF developers should be more transparent with regards to the reference situation modeling hypothesis and tag and bind the reference situations to the CF that is provided. A CF is built on a reference situation and, as such, has a validity of a specific extent. We believe a good practice consists in providing the two parameters $Q_{reference}$ and $Q_{land\ use}$ of the CF so that the CF can be (re)calculated for different reference situations and its parameter of validity can be extended. The CFs could then be used for a greater variety of goal and scopes and actually respond to the LCA vision needs reported by Soimakallio et al. (2015). In our study, we could indeed not include many CFs, as they are commonly only provided as single values. We also acknowledge that providing CFs for several reference situations constitute an additional modeling work.

5 Conclusions

In this work, different reference situations used to derive land impact indicators in LCA are reviewed and a decision tree is provided to guide this modeling choice. We also demonstrated that the choice of reference situation impacts the LCA results and can invert rankings (and conclusions) in a comparative LCA study. The modeling choice affects each impact pathway in a different way and is specific to land cover types and locations. Their use, which originates from a modeling choice made when developing the characterization factors, should therefore be explicit. Further work is required to elucidate the relationships between the reference situations.

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