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LAND USE IMPACTS

Assessing potential desertification environmental impact in life cycle assessment

Part 1: Methodological aspects

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Abstract
Background, aim and scope Life cycle assessment (LCA) enables the objective assessment of global environmental burdens associated with the life cycle of a product or a production system. One of the main weaknesses of LCA is that, as yet, there is no scientific agreement on the assessment methods for land-use related impacts, which results in either the exclusion or the lack of assessment of local environmental impacts related to land use. The inclusion of the desertification impact in LCA studies of any human activity can be important in high-desertification risk regions.
Main features This paper focuses on the development of a methodology for including the desertification environmental impact derived from land use in LCA studies. A set of variables to be measured in the life cycle inventory (LCI), their characterisation factors (CFs) and an impact assessment method for the life cycle impact assessment (LCIA) phase are suggested. The CFs were acquired using a geographical information system (GIS).
Results For the LCI stage it is necessary to register information on: (1) the four biophysical variables of aridity, erosion, aquifer overexploitation and fire risk, with a created scale of values; (2) the geographical location of the activity and (3) the spatial and temporal extension of the activity. For the CFs, the four LCI biophysical variables in (1) were measured for the main terrestrial natural regions (ecoregions) by means of GIS.
Discussion Using GIS, calculation of the CF for the aridity variable shows that 38% of the world area, in eight out of 15 existing ecoregions, is at risk of desertification. The most affected is the tropical/subtropical desert. The LCIA model has been developed to identify scenarios without desertification impact.
Conclusions The developed method makes possible the inclusion of the desertification impact derived from land use in LCA studies, using data generally available to LCA users.
Recommendations and perspectives While this LCIA model may be a simplified approach, it can be calibrated and

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Preamble In this series of two papers, methodological aspects related to the assessment of desertification environmental impact in life cycle assessment (LCA) are discussed (Part 1), and the operational method and characterisation factors suggested are put into practise in a case study of energy crops in different regions worldwide (Part 2).

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improved for different case studies. The model proposed is suitable for assessing the desertification impact of any type of human activity and may be complemented with specific activity indicators, and although we have considered biophysical factors, the method can be extended to socio-economic vectors.

Keywords Aridity index · Characterisation factors · Desertification · Geographical information system (GIS) · Land use impacts · Life cycle assessment (LCA) · Life cycle impact assessment (LCIA) · Life cycle inventory (LCI)

1 Introduction

Life cycle assessment methodology (LCA) was initially developed for environmental assessments of industrial systems. It was later adapted to agricultural systems, where its use has gradually spread. Traditionally, LCA studies take a general approach that is spatially and temporally independent of the environmental impacts derived from a product or production system (ISO-14040 2006; ISO-14044 2006). However, as agricultural systems are closely related to local and temporal aspects, especially water consumption and land use, adjustments of the LCA methodology to take land use impacts into consideration are the subject of study (Guinée et al. 2006) for both the life cycle inventory (LCI) and the life cycle impact assessment (LCIA).

Today, it is acknowledged that land use should be assessed by LCA, but there is still no consensus on the parameters to consider and the methodology to follow, mainly due to the lack of available data (Cowell and Lindeijer 2000). Research has been carried out by a number of authors to identify the possible problems and propose solutions to address land use in LCA (Audsley 1997; Goedkoop et al. 2009; Koellner and Scholz 2007; Koellner and Scholz 2008; Milà i Canals et al. 2007; Wegener Sleeswijk et al. 1996; Weidema and Meeusen 2000).

Apart from the area of land, land use quality and soil disturbance by the activity being developed have to be considered (Guinée et al. 2001; Mattsson et al. 2000; Milà i Canals et al. 2007).

Due to the complexity of the different factors affecting land use quality, most proposals have suggested distinguishing between different ecosystems (Heijungs et al. 1992; Steen and Ryding 1993) and using multiple indicators (Blonk et al. 1997; Cowell and Clift 2000; Mattsson et al. 2000).

1.1 Desertification as a life cycle assessment land use impact category

To date, no attempts to include desertification impact in LCA studies have been published, even though this is one of the main problems for sustainability in arid, semi-arid and dry sub-humid areas, especially in developing countries. The United Nations Convention to Combat Desertification (UNCCD) states that arid, semi-arid and dry sub-humid areas include areas other than polar and sub-polar regions, in which the ratio of annual precipitation to potential evapotranspiration lies between 0.05 and 0.65 (United Nations 1994).

Irreversible soil degradation due to desertification is a concern in arid areas worldwide, as such, it is important to include desertification impact in LCA studies in these areas (Civit 2009). In order to assess such land use impact, it is first necessary to define the variables and to gather quality information about them in the LCI. Other elementary flows required in the LCI are the spatial and temporal extent, and the geographical location. Once the inventory data is gathered, the LCI results have to be characterised in the impact assessment phase.

At present, the international community has not agreed on the methodology that should be followed to select desertification indicators. The main obstacle is that not all indicators are suitable at all scales. Two main factors for selecting the appropriate scale to measure an indicator are the availability of data sets for the area over a sufficient length of time, and the possibility of using remote-sensing technologies to obtain information (DESERTLINKS 2004).

Desertification indicators are arranged according to the three dimensions of sustainable development: environmental (or biophysical), economic and social (MIMAM 2006). Most of the studies on desertification assessment (e.g., DESERTLINKS, DesertNet, DISMED, LADA and MEDALUS) have focused on the biophysical dimension of desertification, using several variables to measure it. Thus, desertification assessment using a multi-indicator approach appears to be an appropriate method for evaluating this land use impact.

1.2 Life cycle assessment and geographical information systems

Nowadays, most desertification indicators included in national action programmes and in studies to combat desertification are directly obtained from digitalized maps or by using geographical information systems (GIS).

Despite the widespread employment of GIS, little use is made of combinations of GIS data with LCIA to obtain land use indicators. Examples of using GIS and LCA focus on handling the information acquired with GIS methods to produce site-specific information on the environmental effects of a product or production system, which allows for more accurate LCA (Bengtsson et al. 1998; Jäppinen et al. 2008).

Given the benefits of GIS to provide land information, and the weakness of LCA, lacking impact categories related to land use, the integration of GIS with LCA is a good tool to define site-dependent characterisation factors (CFs). This improves LCA adaptability to land use impacts, not only for desertification but also for other land use impacts such as biodiversity, water consumption and erosion.

The aim of this research was to develop a methodology for including potential desertification from land use as an environmental impact in LCA studies. This study provides LCI data, CFs obtained by GIS analysis and a LCIA.

2 Life cycle inventory modelling

LCI considers the total consumptions and emissions of a system and quantifies them according to the functional unit established. When considering land use, inputs are related to resource consumption as well as to the pressure put on them.

Inputs to the model proposed must reflect the causes of land degradation, specifically those that affect arid lands, i.e., the causes of desertification. The selection was carried out by overlapping indicators at the local, national and global level and those indicators applicable within the LCA methodology. Only physical factors, belonging to the state and pressure framework, were taken into account, due to the disagreement related to social and economic vectors. The four selected physical variables state the desertification impact due to the different human activities that can occupy a portion of land during a certain period of time. The selected variables were: aridity index, erosion, aquifer overexploitation and fire risk. After an extensive review of action programmes to combat desertification from several countries and a number of international studies focused on assessment of desertification indicators, we concluded that these four variables adequately embrace the main factors that cause desertification. The four variables may be complemented with those specific for different kinds of human activity (e.g., salinity for agricultural activities, soil crusting for building activities). For LCA practitioners wishing to include a specific variable, because it is a basic indicator in a certain region under study, the same procedure must be followed as with the other variables.

Table 1 shows the variables selected for inclusion in the LCI and their possible values. Each one must first be quantified then qualified following the scales of values proposed in Sections 2.1 to 2.4. The proposed values were based on the reviewed desertification programmes and desertification studies.

Once the individual value for each variable has been assigned, the LCI value ($\mathrm{LCI}_{\mathrm{Desertification}}$) can be calculated as shown in Eq. 1:

$$\begin{aligned}&\text{If } V_{\mathrm{Aridity}} \leq 0,\ \mathrm{LCI}_{\mathrm{Desertification}} = 0\\ &\text{If } V_{\mathrm{Aridity}} > 0,\ \mathrm{LCI}_{\mathrm{Desertification}} = V_{\mathrm{Aridity}} + V_{\mathrm{Erosion}}\\ &\qquad + V_{\mathrm{Aquifer\ overexploitation}} + V_{\mathrm{Fire\ risk}}\end{aligned} \quad (1)$$

where $\mathrm{LCI}_{\mathrm{Desertification}}$ is the desertification index for the LCI phase and V_{Aridity}, V_{Erosion}, $V_{\mathrm{Aquifer\ overexploitation}}$ and $V_{\mathrm{Fire\ risk}}$ are the individual values for each variable. The sum of the individual values for the four variables was used to express the desertification impact caused by an activity, following the United Nations definition of desertification (United Nations 1994), even though other mathematical formulae may also be appropriate. As a general rule, the higher the $\mathrm{LCI}_{\mathrm{Desertification}}$ value, the greater the desertification impact; however, Section 2.1 reports an exception to this generalisation. This LCI framework allows for easy comparisons of the desertification impact of several activities under study.

As Table 1 shows, the range between the higher and the lower values of each variable differs. While $V_{\mathrm{Aquifer\ overexploitation}}$ and $V_{\mathrm{Fire\ risk}}$ range from 1 to 2, the range for V_{Aridity} is from 0 to 3 and V_{Erosion} from 1 to 3. Only V_{Aridity} can take a value of 0. A different weighting was assigned to the conditions considered in each variable, depending on their importance in determining desertification. Both $V_{\mathrm{Aquifer\ overexploitation}}$ and $V_{\mathrm{Fire\ risk}}$ have a lower weighting than V_{Aridity} and V_{Erosion}. The aridity variable has a higher weighting as it is the criterion used by the United Nations (1994) to identify those zones where desertification could occur. The high weighting allocated to soil erosion is due to its major impact at a global level. In addition, both the aridity index and soil erosion are the two basic indicators in all national action programmes to combat desertification (DESERTLINKS 2004). Following the criterion established in the Spanish Desertification National Action Programme (DNAP-Spain), four desertification impact categories were distinguished in agreement with the $\mathrm{LCI}_{\mathrm{Desertification}}$ value: low ($\mathrm{LCI}_{\mathrm{Desertification}}$ from 4 to 5), medium ($\mathrm{LCI}_{\mathrm{Desertification}}$ from 5 to 6), high ($\mathrm{LCI}_{\mathrm{Desertification}}$ from 6 to 7) and very high ($\mathrm{LCI}_{\mathrm{Desertification}}$ from 7 to 10).

Apart from the individual values for each variable (V_{Aridity}, V_{Erosion}, $V_{\mathrm{Aquifer\ overexploitation}}$ and $V_{\mathrm{Fire\ risk}}$), to assess this impact of land use it is necessary to register the geographical location, and spatial and temporal extension of the activity in the LCI.

2.1 Aridity variable

The aridity factor was calculated considering the climatic surface map given by the ratio P/ET_0, where P is the precipitation and ET_0 the potential evapotranspiration. General criteria to characterise each area are shown in Table 1.

To assign values to the aridity variable (V_{Aridity}), the regions described within the United Nations definition of desertification (United Nations 1994) were considered. According to the UNCCD, humid sub-humid and humid areas are not at risk of desertification. The numerical values assigned were: arid regions, 3; semi-arid regions, 2; dry

Table 1 Proposal for the estimation and evaluation of desertification variables for the inventory phase ($LCI_{Desertification}$; dimensionless)

Desertification variables	
Estimation value	Evaluation (LCI variable data, dimensionless)
Aridity variable ($V_{Aridity}$)[a]	
Arid (0.05–0.20)	3
Semi-arid (0.20–0.50)	2
Dry sub-humid (0.50–0.65)	1
Humid sub-humid (0.65–0.75)	0
Humid (>0.75)	0
Erosion variable ($V_{Erosion}$)	
>25 $tha^{-1}year^{-1}$	3
12–25 $tha^{-1}year^{-1}$	2
<12 $tha^{-1}year^{-1}$	1
Aquifer overexploitation variable ($V_{Aquifer\ overexploitation}$)	
W[b]>0.8R[c]	2
0.8R≥W>0.4R	1.6
0.4R≥W>0.2R	1.3
W≤0.2R	1
Fire risk variable ($V_{Fire\ risk}$)	
≥10% burned area in previous 10 years	2
<10% burned area in previous 10 years	1

[a] Ratio between precipitation (P) and evapotranspiration (ET_0; P/ET_0), dimensionless

[b] Withdrawal

[c] Recharge

sub-humid regions, 1 and humid sub-humid and humid regions, 0. These numerical values were adapted from the DNAP-Spain proposal. This action programme gives arid regions a value of 2, semi-arid regions a value of 1 and the remainder (dry sub-humid, humid sub-humid and humid regions) a value of 0. However, it seems more appropriate to increase the value of all climates with desertification risk, from dry sub-humid to arid regions, by one unit. Regardless of the $V_{Erosion}$, $V_{Aquifer\ overexploitation}$ and $V_{Fire\ risk}$ values, the desertification impact in a portion of land exists only if $V_{Aridity}$ is not equal to 0, as shown in Eq. 1.

2.2 Erosion variable

Erosion is one of the main reasons for soil degradation and desertification. The LCI data for the erosion variable ($V_{Erosion}$) only requires an estimate of water erosion for the study area. Wind erosion is not included in the measurement because, by comparison, water erosion causes greater soil losses on a world scale (Oldeman et al. 1990; Reich et al. 2001). Water erosion is a biophysical indicator usually built within the national action programmes to combat desertification. The universal soil loss equation (USLE; Wischmeier and Smith 1978) was used for the assessment, as it is the quantitative model of soil loss evaluation with the greatest agreement on an international level and widely applied (Boellstorff and Benito 2005; Nelson 2002; Van der Knijff et al. 2000). The USLE predicts the average annual water erosion rate in the long-term on a field slope based on rainfall pattern, soil type, topography, crop system and management practises. In this study, the five erosion intensity categories proposed by Stone (2000) were reduced to three: category 1 (<12 $tha^{-1}year^{-1}$) combines the <7.5 and 7.5–12.5 $tha^{-1}year^{-1}$ categories, category 2 (12–25 $tha^{-1}year^{-1}$) corresponds to the 12.5–25.5 $tha^{-1}year^{-1}$ category and category 3 (>25 t $ha^{-1}year^{-1}$) combines the 25.5–37 and >37 $tha^{-1}year^{-1}$ categories. These three categories were given the numerical values of 1, 2 and 3 respectively, following the DNAP-Spain criteria. The established thresholds fit well within those adopted by DNAP-Spain and are similar to those suggested by other authors: Basic et al. (2004) considers six categories, from <2 $tha^{-1}year^{-1}$ (insignificant erosion) to >40.01 $tha^{-1}year^{-1}$ (disastrous erosion) and Kirkby et al. (2004) distinguishes eight erosion limits, from ≤0.5 $tha^{-1}year^{-1}$ to >50 $tha^{-1}year^{-1}$.

2.3 Aquifer overexploitation variable

Overexploitation may be defined as the situation in which, over a period of years, the average aquifer abstraction rate is greater than, or close to, the average recharge rate (RDPH 1986). The LCI data estimate for the aquifer overexploitation variable ($V_{Aquifer\ overexploitation}$) needs to take into account the hydrological balance of the aquifers located in the area under study. The variable can take four different values, between 1 and 2, depending on the degree of aquifer exploitation, calculated as withdrawal divided by recharge (water exploitation ratio). The aquifer exploitation thresholds established in this study are based on those suggested by Alcamo et al. (2000). For this author, an exploitation ratio above 0.8 indicates very high stress ($V_{\mathrm{Aquifer\ overexploitation}}$ is 2); a ratio between 0.4 and 0.8 represents high stress ($V_{\mathrm{Aquifer\ overexploitation}}$ is 1.6); a ratio between 0.2 and 0.4 indicates medium stress ($V_{\mathrm{Aquifer\ overexploitation}}$ is 1.3); a ratio between 0.1 and 0.2 means low stress; and a ratio below 0.1 shows no stress ($V_{\mathrm{Aquifer\ overexploitation}}$ is 1 in these last two cases). Currently, there is no objective basis for selecting a threshold for overexploitation ratio. The DNAP-Spain considers that aquifer overexploitation only takes place when water withdrawal is equal or higher than 0.8 times the recharge. However, other authors consider this exploitation rate shows high-stressed water resources. For this reason, the criterion of the DNAP-Spain was rejected in favour of more universal and conservative criteria for water requirements of ecosystems.

2.4 Fire risk variable

Forest fires, recognised as a cause of desertification (MIMAM 2005), are one of the main factors that influence the structure and function of terrestrial ecosystems all over the world. The LCI data for the fire risk variable ($V_{\mathrm{Fire\ risk}}$) was obtained by quantifying the accumulated percentage of surface affected by forest fires during the last 10 years in the geographical area under study. If these data are not available, statistical data over a period of 10 years may be used. The selected geographical area must be equivalent to a regional administrative division (e.g., departamentos, comarcas in Spain and Argentina). The choice of the 10-year period for the fire statistics was based on the monitoring period of the Forest Resources Assessment 2005 (1988–1992 and 1998–2002; FAO 2006). Fire intensity was classified into two groups, following the DNAP-Spain criterion: <10% of affected area and ≥10% of affected area. According to this criterion, when the area affected is <10%, the fire risk variable takes a value of 1, and when it is ≥10%, the variable takes a value of 2. The 10% threshold is also considered appropriate for regions outside Spain because this value was the result of a consensus agreed in an action programme to combat desertification in a Mediterranean region. Here, many studies on the consequences of fires have been carried out, as a consequence of high fire frequency and its derived economic and social problems.

3 Development of the characterisation factors for natural areas

As CFs of the LCIA phase for the four variables estimated in the LCI have been established for the large natural areas of the world, soil quality was taken into account in land use assessment, following the proposals by other authors (Heijungs et al. 1992; Steen and Ryding 1993). CFs for large natural areas that incorporate biodiversity impacts in LCA have also been developed (Cowell and Lindeijer 2000; Koellner 2000; Schmidt 2008), but no inclusion of desertification impacts has previously been published. One of the main contributions of this study is the establishment of desertification impact CFs for the large natural areas of land. The divisions between these areas are based on climatic and vegetative cover factors, both aspects having a major influence on soil desertification risk.

3.1 Choice of an ecosystem classification

The assessment of any impact category in LCA requires CFs that are unique on a global scale. To satisfy this premise, the classification of natural systems that is used in the LCIA must comply with the following criteria: (1) it must be applicable worldwide, (2) it needs to be accepted by the scientific community and widely used, (3) the data must be available worldwide and (4) a relationship between each natural system category and its desertification risk must be shown. Additionally, it is preferable that the classification is available in digital format, to enable work with GIS.

Many authors have developed classification systems of natural areas. For example, Begon et al. (1999) define 12 biomes, Folch et al. (1984) distinguish 12 physiognomic domains, Olson et al. (1983) identify 44 land ecosystem classes and Bailey (1996; 1998) describes 15 ecosystem regions (or ecoregions). These authors all comply with the four requirements mentioned above, but the hierarchical classification of Bailey's ecoregions was used here as it is available in a GIS compatible format, while the other three have poor quality digitalized public maps. The lack of geo-referenced maps makes it difficult to determine the CFs in the analyses, and to combine the natural areas layer with other information layers (aridity index, erosion risk, aquifer overexploitation and fire risk).

Based on macroclimate conditions and the prevailing plant formations determined by these conditions, Bailey (1996; 1998) subdivided the continents into ecoregions with three levels of detail: domains (macroecosystems), divisions and climate subtypes, provinces or sites (micro-ecosystems; Bailey 2002). Table 3 in the Appendix lists climate, vegetation and surface area associated with each of the four domains and 15 divisions.

3.2 Calculation of the characterisation factors

The CFs must be calculated for each LCI variable and for each ecoregion. The assessment methodology and the possible values follow the same procedure used to obtain the values of the variables in the LCI (see Sections 2.1 to 2.4). The CFs were calculated using GIS. The configuration of each layer (one for each variable) was based on the collection of maps and statistical data from several information sources:

$CF^i_{Aridity}$ (characterisation factor for the aridity variable for each ecoregion, *i*) was based on the global aridity index map of the Global Agro-Ecological Zoning 2000 from FAO and IIASA (Fischer et al. 2000).

$CF^i_{Erosion}$ was derived from the world map of the Global Assessment of Human-Induced Soil Degradation (GLASOD; ISRIC 2008). In GLASOD, a total of 12 soil degradation types are recognised and mapped, of which two types are related to water erosion: loss of topsoil (Wt) and terrain definition/mass movement (Wd). Both were accounted for in each ecoregion in order to obtain the $CF^i_{Erosion}$.

$CF^i_{Aquifer\ overexploitation}$ was determined using statistical data on the recharge and withdrawal aquifer exploitation rates per country published by EEA (1999), EMWIS (2007), FAO (2007a), UNEP (2002) and WRI (2007). These five groups collected their data for years between 1960 and 2007. However, the years covered for statistical analysis are variable and typically not available for a time series.

$CF^i_{Fire\ risk}$ was also derived from statistical data at the national level published by FAO (2006; 2007b; 2008) and

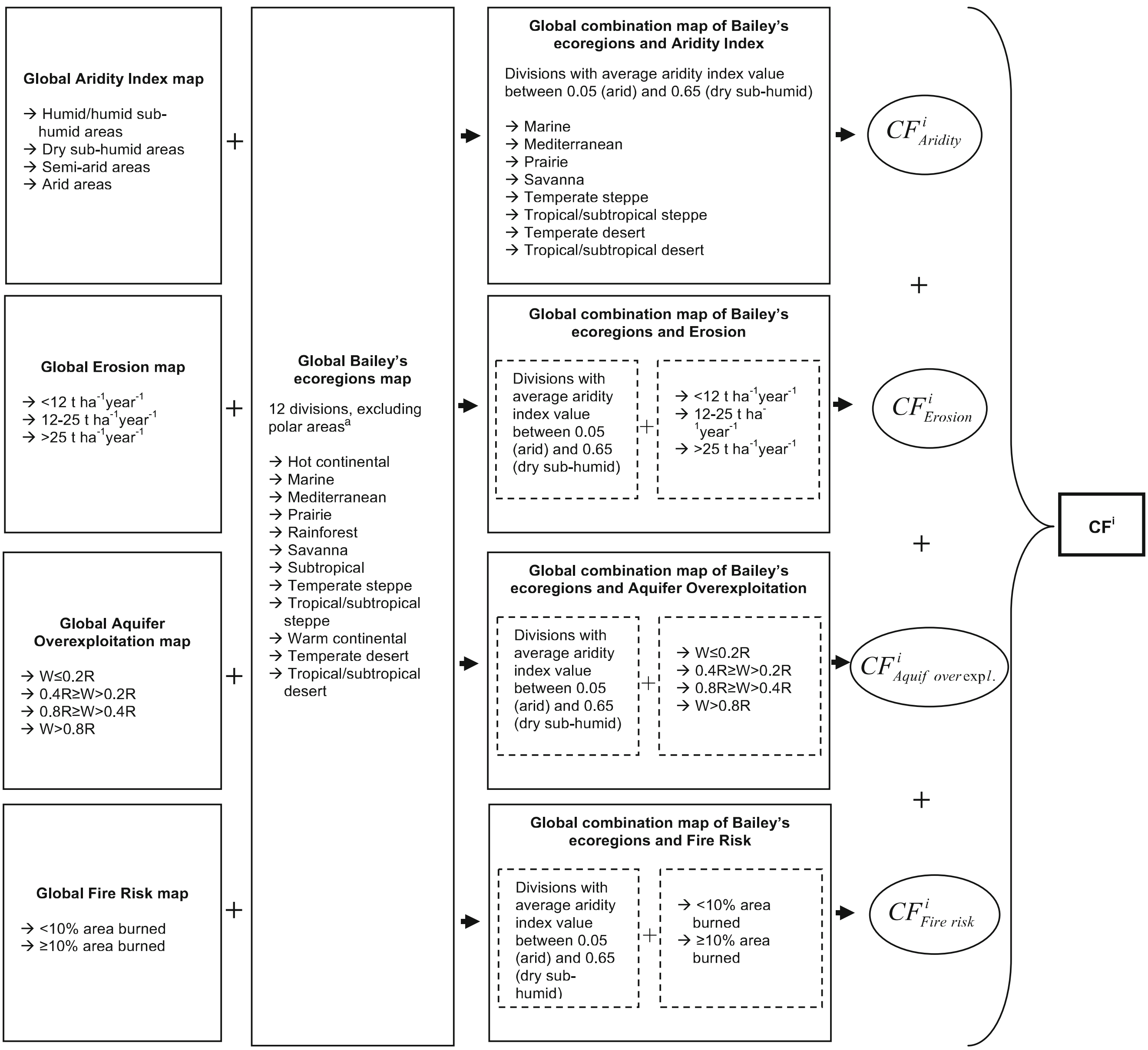

Fig. 1 Diagram of the methodology applied for obtaining the characterisation factors of desertification risk for each ecoregion (CF^i). [a] Three divisions of the polar domain (icecap, tundra and subarctic) were not included as they are in a cold or antarctic climate (not arid, semi-arid or dry sub-humid areas; Fischer et al., 2000). *i* ecoregion, *CF* characterisation factor

UNEP (2002). The statistical period covered is from 1985 to 2004. In countries where data on the surface affected by forest fires for a period of 10 years was not available, the average burned area per year was calculated from the available information.

Once the information on each of the four variables was compiled, geo-referenced layers were made using GIS. For this, we used two software programmes: MiraMon® 6.1 (2008) and ArcView 3.2®. The GIS allows the overlap of Bailey's ecoregions layer with the four desertification variable layers, to obtain surface statistics of each variable category for each ecoregion.

$CF^{i}_{\mathrm{Aridity}}$ and $CF^{i}_{\mathrm{Aquifer\ overexploitation}}$ were calculated as the average value for each ecoregion. $CF^{i}_{\mathrm{Erosion}}$ is the average value of soil erosion risk in the ecoregion soils threatened by water erosion, weighted by the ecoregion surface area. Finally, $CF^{i}_{\mathrm{Fire\ risk}}$ was calculated by a similar method to that applied in the LCI phase, in which an ecoregion is considered to have a fire risk (CF is 2) if, during the previous 10 years, a minimum of 10% of its surface area had been affected by fires, with each country affected having a ratio equal to or higher than 10% of area burned. If the burned area of the ecoregion is lower than 10%, its CF is 1.

The CF for a given ecoregion can be calculated as the sum of the CFs for each of the four variables. The methodology explained in this section is summarised in Fig. 1. As shown in this figure, after carrying out the overlap between the Global Aridity Index map and the Global Bailey's Ecoregions, only eight out of 15 ecoregions have arid, semi-arid or dry sub-humid average aridity index. These ecoregions are: marine, Mediterranean, prairie, savanna, temperate steppe, tropical/subtropical steppe, temperate desert and tropical/subtropical desert, which represent 38% of the total land surface. According to the United Nations (1994) criterion, desertification risk is only possible in these eight ecoregions. In the remaining seven ecoregions, $CF^{i}_{\mathrm{Aridity}}$ is equal to 0 (see Section 2.1 and Table 1).

Information from GIS technology was directly applicable to the LCA in this research, allowing the calculation of the CFs for the LCIA phase. Therefore, the simultaneous use of these tools (LCA and GIS) has clear advantages for retrieving information on land use impact. Figure 2 shows one of the four GIS layers.

4 Life cycle impact assessment modelling

4.1 Application of characterisation factors

Table 2 shows the CFs for each variable and ecoregion division with desertification risk. These CFs were obtained by applying the methodology described in Fig. 1 and the variable values estimated in the LCI data phase (see Section 2 and Table 1).

The greatest desertification risk is found in the tropical/subtropical desert ecoregion, with a CF of 7.6 (out of 10). This ecoregion is mainly located in northern countries of Africa, some Arabian countries, Australia, the southwest of China and the western edge of South America. Terrestrial deserts (hyper-arid areas where precipitation is lower than 25 mm year^{-1}) and semi-deserts (areas with imminent desertification risk) are located within this ecoregion.

Mediterranean and tropical/subtropical steppe (both with a value of 6.3) are the ecoregions with the next greatest desertification risk, while marine and prairie are, among all

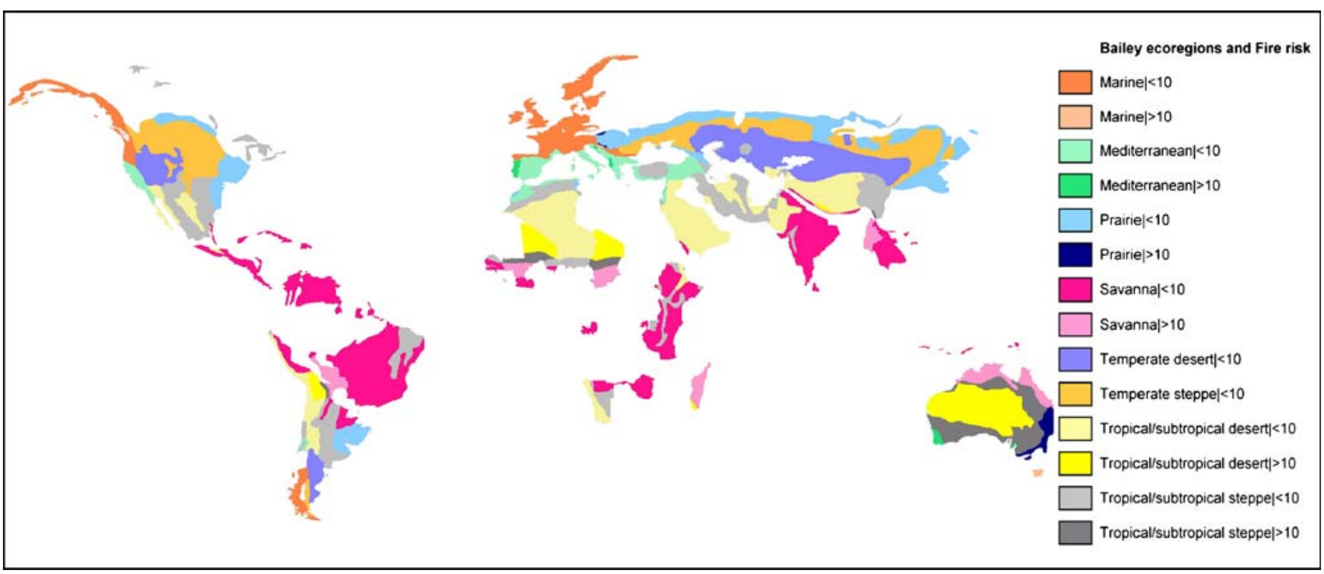

Fig. 2 Global combination map of Bailey's ecoregions with fire risk

Table 2 Characterisation factors of desertification risk for each ecoregion (dimensionless)

	Marine	Prairie	Temperate steppe	Temperate desert	Savanna	Mediterranean	Tropical/subtropical steppe	Tropical/ subtropical desert
$CF_{Aridity}$	1	1	2	2	1	1	2	3
$CF_{Erosion}$	1	1	1	1	2	2	1	2
$CF_{Aquifer\ overexploitation}$	1	1	1	1.3	1	1.3	1.3	1.6
$CF_{Fire\ risk}$	1	1	1	1	2	2	2	1
CF^i	4.0	4.0	5.0	5.3	6.0	6.3	6.3	7.6

i ecoregion

the ecoregions with desertification risk, the least susceptible (CF of 4).

4.2 Life cycle impact assessment model

In this study, we also propose a desertification impact assessment model. Equation 2 shows the model proposed for inclusion in LCA studies.

$$\mathrm{LCIA_{Desertification}} = \left[\mathrm{LCI_{Desertification}} \times \mathrm{CF}^i\right] \times \frac{\mathrm{Area_{LCI\ activity}}}{\mathrm{Log\ Area_{Ecoregion}}_{\ i}} \times t \qquad (2)$$

where $\mathrm{LCIA_{Desertification}}$ is the desertification impact due to the assessed activity, in $\mathrm{km^2}_{\mathrm{LCI\ activity}} \times \mathrm{km^{-2}}_{\mathrm{Ecoregion}\ i}$ during the period of time (years) that the activity takes place; $\mathrm{LCI_{Desertification}}$ is the inventory data (dimensionless) of this activity; CF^i is the characterisation factor of the ecoregion where the evaluated activity takes place (dimensionless, see Table 2); $\mathrm{Area_{LCI\_Activity}}$ is the spatial extension of the activity (in $\mathrm{km^2}$); Log $\mathrm{Area_{Ecoregion\_}}_i$ is the decimal logarithm of the ecoregion area where the activity is located (in $\mathrm{km^2}$) and t is the temporal extension of the activity (in years). High values of $\mathrm{LCIA_{Desertification}}$ mean high soil desertification impact caused by the situation under analysis.

It should be noted that, when the variable V_{Aridity} in the $\mathrm{LCI_{Desertification}}$ is equal to 0 (humid climates, without desertification risk), $\mathrm{LCIA_{Desertification}}$ is zero. In this case the desertification impact of the activity should not be integrated in LCA studies. This can be used to identify those cases without desertification impact. The $\mathrm{LCIA_{Desertification}}$ value is also zero when CF^i or any other variable in Eq. 2 is zero. A value of zero for CF^i means that the activity being studied is in an ecoregion with no desertification risk (icecap, tundra, subarctic, warm continental, hot continental, subtropical and rainforest).

The model suggested focuses on the desertification risk value of the ecoregions without comparing to a reference ecoregion (Blonk et al. 1997; Heijungs et al. 1992; Weidema et al. 1996). This approach works well, as there is no agreement about which reference system to select or how to measure it.

The LCIA model selected was that which fit best the models used to apply in LCA of those tested. Previous LCIA models tested were, for instance, the average $\mathrm{LCI_{Desertification}}/\mathrm{CF}^i$ and the weighted average $\frac{\sum_{i=1}^{n} V_{\mathrm{LCI\ variable}}}{\sum_{i=1}^{n} \mathrm{CF}^i_{\mathrm{variable}}}$ approaches. They were not effective in cases of single land use (activities with the same LCI) in different ecoregions. In both approaches the greatest impact values were obtained in ecoregions with lower CF.

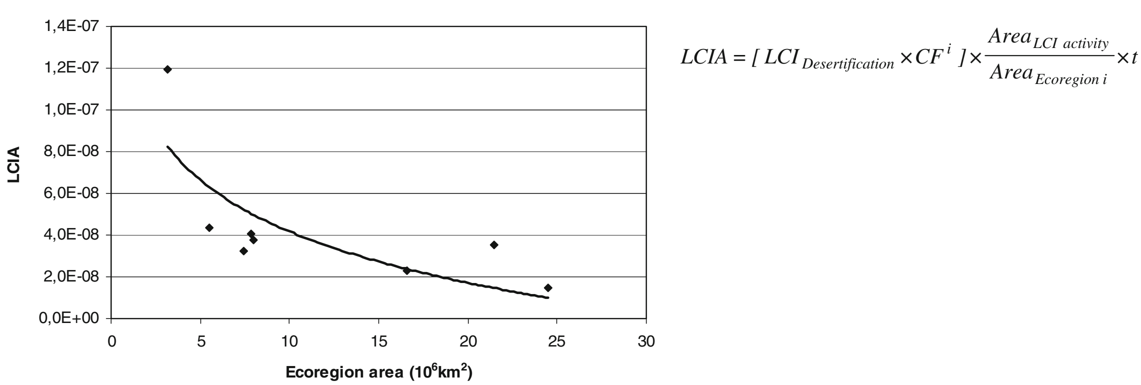

Fig. 3 Relationship between the desertification impact (LCIA, in $\mathrm{km^2}_{\mathrm{LCI\ activity}} \times \mathrm{km^{-2}}_{\mathrm{Ecoregion}\ i} \times y$) and the ecoregion area for the eight ecoregions with desertification risk. Hypothetical case where $\mathrm{LCI_{Desertification}}=6$, $\mathrm{Area_{LCI\ activity}}=10{,}000\ \mathrm{m^2}$, $t=1$ year

The area of the ecoregion ($Area_{Ecoregion\ i}$) is expressed in Eq. 2 by a logarithmic relationship with the resulting impact. The aim was to represent the likelihood of an area–desertification relation, with smaller surface areas having more desertification risk than larger areas (Fig. 3). Logarithmic correlations between area–species interactions have been reported for several groups of organisms (theory of insularity), where the drop in the number of species is faster in smaller areas (Begon et al. 1999). It could be argued that the potential impact does not follow an area–desertification relation in a logarithmic way. However, unlike the linear model, the model proposed shows the growing marginal effects with successive surface area reductions.

5 Conclusions

In this research, an LCA methodology for assessing the environmental local impact of desertification were developed and adapted. The approach adds an innovative contribution, since previous LCA methodological studies consider water consumption, erosion and biodiversity impacts but not the desertification impact.

Four biophysical variables belonging to the state and pressure frameworks were selected for the model: aridity, erosion, aquifer overexploitation and fire risk. The desertification impact evaluation of any human activity in a LCA should include these common, basic four variables. The $LCI_{Desertification}$ value of the activity being assessed is determined by the addition of the individual values given to each of the four variables, according to a scale of values.

Following methodologies proposed by other authors to include local biodiversity impacts in LCA, we established CFs of desertification impact for the large divisions of the terrestrial ecological regions (ecoregions). This study is the first we are aware of, at an international level, to include desertification impact in LCA based on a classification of natural areas. GIS technology has facilitated the development of this study. The simultaneous use of LCA and GIS is a major advantage for gathering information that can be applied to decision-making in land management. The calculation of the CF for the aridity index shows that only eight out of 15 terrestrial ecoregions have desertification risk, as their prevailing climate is arid, semi-arid or dry sub-humid. These eight ecoregions are: marine, prairie, Mediterranean, savanna, temperate steppe, temperate desert, tropical/subtropical steppe and tropical/subtropical desert, which represent 38% of the terrestrial surface. The greatest desertification risk is found in the tropical/subtropical desert ecoregion and the lowest in marine and prairie divisions.

All the information required for a desertification impact assessment in the LCA is generally available. This paper provides CFs for including desertification impact in LCA studies, and the variables suggested allow the comparison of the benefits and threats posed by different human activities.

6 Recommendations and perspectives

Although the LCIA model developed as a product of factors may be a simplified approach, it can be calibrated and improved when applied to specific case studies.

The proposed LCI variables are appropriate for assessing the desertification impact of any human activity (agriculture, industry, mining, etc.). The scheme proposed could be complemented with specific LCI factors for different human activities (e.g., salinity for agricultural activities, soil crusting for building activities).

Even though we have considered biophysical variables, the method could be extended to social and economic vectors. However, this is a long-term task due to its magnitude and difficulty.

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Appendix

Table 3 Climate, vegetation and surface area for each ecoregion division

Name of domain	Name of division	Equivalent Köppen-Trewartha climates	Zonal vegetation	Surface area ($10^6 km^2$)
Polar (100)	Ice cap (110)	Polar climate: ice cap		15.40[a]
	Tundra (120)	Polar climate: tundra	Ice and stony deserts: tundras	14.90
	Subarctic (130)	Boreal climate: subarctic	Forest tundras and open woodlands; taiga	16.80

Table 3 (continued)

Name of domain	Name of division	Equivalent Köppen-Trewartha climates	Zonal vegetation	Surface area ($10^6 km^2$)
Humid temperate (200)	Warm continental (210)	Temperate climate: temperate continental, cool summer	Mixed deciduous–coniferous forests	4.34
	Hot continental (220)	Temperate climate: temperate continental, warm summer	Broad-leaved forests	2.56
	Subtropical (230)	Subtropical climate: humid subtropical	Broad-leaved coniferous evergreen forests; coniferous broad-leaved semi-evergreen forests	4.91
	Marine (240)	Temperate climate: temperate oceanic	Mixed forests	4.78
	Prairie (250)	Subtropical climate: humid subtropical; temperate climate: temperate continental, warm summer; temperate climate: temperate continental, cool summer	Forest-steppes and prairies; savannas	3.90
	Mediterranean (260)	Subtropical climate: subtropical dry summers	Dry steppe; hard-leaved evergreen forests; open woodlands and shrub	2.83
Dry (300)	Tropical/subtropical steppe (310)	Dry climate: tropical/subtropical semi-arid	Open woodland and semi-deserts; steppes	13.94
	Tropical/subtropical desert (320)	Dry climate: tropical/subtropical arid	Semi-deserts; deserts	17.98
	Temperate steppe (330)	Dry climate: temperate semi-arid	Steppes; dry steppes	6.84
	Temperate desert (340)	Dry climate: temperate arid	Semi-deserts and deserts	6.78
Humid tropical (400)	Savanna (410)	Tropical and humid climate: tropical wet-dry	Open woodlands, shrubs and savannas; semi-evergreen forest	20.54
	Rainforest (420)	Tropical and humid climate: tropical wet	Evergreen tropical rain forest	12.50

The identification code for each domain and division is shown in parentheses. Source: Bailey (2002)

[a] Includes Antarctica

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