LCA Methodology

LUCAS – A New LCIA Method Used for a CAnadian-Specific Context

Laurence Toffoletto, Cécile Bulle, Julie Godin, Catherine Reid and Louise Deschênes*

CIRAIG – Interuniversity Reference Center for the Life Cycle Assessment, Interpretation and Management of Products, Processes and Services, École Polytechnique de Montréal, P.O Box 6079, Montreal, Quebec, H3C 3A7, Canada

* **Corresponding author** (louise.deschenes@polymtl.ca)

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Abstract

Goal, Scope and Background. Canadian LCA practitioners currently use European or American methodologies when conducting comprehensive impact assessments, despite the fact that these methods may not be appropriate for Canadian conditions. Due to the lack of suitable models that are currently available, work has been undertaken to develop an LCIA method by adapting existing LCIA models to the Canadian context. This new method allows the characterization of 10 impact categories.

Methods. This project is strongly based on preliminary outcomes from SETAC recommendations for the best available practices in LCIA. Models from 3 recent LCIA site-dependent methods, EDIP2003, IMPACT2002+ and TRACI, were used in this midpoint Canadian-specific method. Characterization models were chosen based on their level of comprehensiveness, scientific sophistication and the possibility of integrating site-specific values in the models.

Results and Discussion. All regional and local impact categories in the method are site-differentiated. For aquatic eutrophication, (eco)toxicity and land-use impact categories, regionally-differentiated models taking into account fate and effect were already available: the parameters of these models were modified for the Canadian context. For acidification, aquatic and terrestrial eutrophication, existing models were spatially differentiated for fate: regionalization of the effect factor was also included, based on the level of sensitivity of each ecozone assessed with vulnerability factors. The default spatial resolution selected for this method was Canadian ecozones, which define spaces in an ecologically meaningful way where organisms and their physical environment evolve as a system. For each ecozone, 2334 site-dependent characterization factors have been calculated.

Conclusion. This LCIA methodology proposes an attractive and useful set of site-dependent characterization factors for the 15 Canadian terrestrial ecozones.

Recommendation and Outlook. Efforts are being carried out to extend the specificity of some factors used in eutrophication modelization. The transparency of the methodology will allow to recalculate site-dependent characterization factors for different regions and for additional substances.

Keywords: Canadian terrestrial ecozones; characterization factors; LCIA method; LUCAS; site-dependency; vulnerability factors

Introduction

Recently, spatial differentiation has been considered as a subject of improvement for LCIA methods and their characterization models for local and regional impacts. It is generally recognized, depending on the goal and scope of the LCA study, that using region-specific and time-specific characterization factors in the case of impact categories such as acidification, eutrophication (aquatic and terrestrial), photochemical smog, toxicity, ecotoxicity and land-use might be useful (Pennington et al. 2004, Hauschild et al. 2003, Norris, 2003, Huijbregts et al. 2000). However, there is no worldwide consensus on which site-specific models should be used by stakeholders (Udo de Haes et al. 2002) and accounting spatial differentiation in LCIA remains complicated due to the lack of spatial distinction in most emissions and resource consumption inventory databases. Within the past 3 years, site-specificity in LCIA methods has increased significantly. No less than 4 methods have been released which include site-specificity in their characterization models at midpoint or damage levels (Table 1), but none of these methods can be applied to a Canadian geographical context without integrating a significant uncertainty.

Despite what Young (2003) said could be termed as a rediscovery, Canada does not have characterization factors specific to its geographical context, thus far. The recent increase in LCA studies in Canadian industries and small and medium enterprises have placed the development of Canadian characterization factors at the forefront of LCA development in Canada. Most of the Canadian LCA studies published in the last 5 years use either generic characterization factors (Godin et al. 2004, Ménard et al. 2004, Toffoletto et al. 2005) or simplified LCIA with only a quantification of emissions (Diamond et al. 1999). Stakeholders can also conduct LCIA in Canada using USEPA's TRACI method with US characterization factors. TRACI has the advantage of considering all North-American territory in some of its deposition models (Bare et al. 2003). Nevertheless, this still implies using site-specific factors that are not completely appropriate to the geographical context of the study. TRACI

Table 1: Site-dependent LCIA methods released in the last 3 years

LCIA methods	Number of impact categories	Level of specificity	References
EDIP2003	8 midpoint categories	European countries	Hauschild et al. 2003
IMPACT2002+	14 midpoint categories and 4 damage categories	European countries	Jolliet et al. 2002
LIME	11 midpoint categories and 16 damage categories	Japan regions	Itsubo and Inaba 2003
TRACI	12 midpoint categories	US states	Bare et al. 2003

uses data that are not available for Canada and, hence, cannot simply be adapted to its geographical context. For instance, the topological network model and composite runoff field model outputs used in TRACI for the fate aquatic eutrophication model could not be found for Canada. As a result, Canadian method developers were forced to choose other characterization models for which data could be generated in Canada. With the help of SETAC recommendations (Udo de Haes et al. 2002) and with the establishment of a list of selected criteria, more appropriate models were chosen among other non-North-American methods such as EDIP2003 (Hauschild et al. 2003) or IMPACT2002+ (Jolliet et al. 2002). LUCAS (LCIA method Used for a CAnadian-Specific context) originated from this necessity of having Canadian-specific characterization factors. The following paper presents the characterization models selected for LUCAS. Since most of the models have already been presented in specific papers, details on the calculation procedures have been omitted, and only the required adaptations made have been included.

1 General Framework

1.1 Impact category selection

The first step in developing this new LCIA method was to select the impact categories that would be characterized. SETAC recommendations (Udo de Haes et al. 2002) were strictly followed and only categories having models with consensus approved indicators were selected. The categories of odour, noise, radiation and biotic resources were not characterized in LUCAS in this first phase of development; although further improvements are underway so that these impacts will eventually be taken into consideration. The present version of LUCAS proposes characterization factors for the following 10 impact categories: (1) climate change; (2) ozone depletion; (3) acidification; (4) smog formation; (5) aquatic eutrophication; (6) terrestrial eutrophication; (7) ecotoxicity (aquatic and terrestrial); (8) toxicity; (9) land-use and (10) abiotic resource depletion. Although there is no consensus on the terrestrial eutrophication category indicator (Potting et al. 2002), this impact covers effects of large interest in Canada because of large natural areas and was, hence, included in LUCAS. Moreover, assessment of nitrogen (N) and phosphorus (P) loading from Canadian sources has revealed that nutrients are causing problems in selected Canadian freshwater, coastal, and forest ecosystems and affecting the quality of life of many Canadians (Chambers et al. 2001).

1.2 Criteria selection for characterization models

The second step in the development of LUCAS was to review site-specific methods for each impact category and to analyze how characterization models integrate site-specificity. As recommended by SETAC (Udo de Haes et al. 2002) and Bare et al. (2000), the LUCAS methodology will ultimately propose midpoint and damage characterization factors as IMPACT 2002+ does (Jolliet et al. 2003). As a first step, only midpoint characterization models were selected, keeping in mind that damage factors would have to be developed in a compatible framework in future developments. Since IMPACT 2002+ was selected for the ecotoxicity and toxicity impact categories in LUCAS, both midpoint and damage factors were already available for these two categories.

Because of the invariable presence of value judgements in any LCIA, there is no unique, best method for conducting an impact assessment (Hertwitch et al. 2000). Therefore, method developers have to determine certain criteria which they judge to be the most important in order to select a characterization model. The main criteria specific to LUCAS are presented in **Table 2**. They cover general, spatial and temporal aspects. These specific criteria were added to those

Table 2: Main selection criteria used for the development of LUCAS

	Criteria	Description
General Aspects	Chemical coverage	High number of characterized chemicals (in percentage for instance)
	Presence of sub-categories	Sub-categories are in the model
	Frequency of use in LCIA methods	The model is used in more than one method
	Scientific and technical validity	The model represents the environmental mechanisms
	Focal point in environmental mechanism	Midpoint models were preferred compared to damage
	Presence of model linking midpoint to damage in the case of midpoint model	The midpoint model is related to a damage model
	Validity of the model for each chemical substance that contributes to the impact	Model is reliable for each chemical as opposed to one or more substances having a different fate or effect than the ones modelized
	Level of inventory sophistication required	The model does not require very specific inventory data
Spatial Aspects	Spatial parameters	Presence of spatial parameters in the model calculations
	Quantity of spatial parameters	Number of parameters, if any
	Adapted spatial resolution scale	The resolution scale proposed in the model is coherent with environmental mechanisms
Temporal Aspects	Temporal parameters	Some temporal parameters are in the model calculations
	Temporal scale	The temporal scale proposed in the model is coherent with environmental mechanisms
	Temporal scale modification	The temporal scale can be modified
	Time integration	There is integration over time
	Seasonal variations	Seasonal variations are taken into account
Implementation and adaptation to different geographical contexts	Validity of the model for different geographical contexts	A resolution scale modification can be applied
	Transparency and easy adaptation	There is enough available information to adapt the model to a different spatial context
	Data availability for adaptation to another resolution scale	There is available data for the modification of the spatial context

recommended by ISO 14042 (ISO 2000) and SETAC (Udo de Haes et al. 2002) which include, for instance, international acceptance, environmental relevance, fate, exposure and effects models and uncertainty margins.

A general concern in selecting the models was: how does one make a fair compromise between the sophistication level of the model and the resources required to complete the model calculations? As mentioned in Hertwich et al. (2000), the more demanding the LCIA, the less it will be used. Table 2 illustrates that data availability was a key element in selecting a model, even if a more sophisticated model was available. The authors wanted LUCAS to be useable in Canadian LCA studies while remaining user-friendly. Another parameter that was kept in mind in selecting the models was that the calculation of new characterization factors (for a new substance or a new region) had to be simple. The authors wanted a flexible and transparent method which allowed for easy recalculation of characterization factors. Ease in changing spatial resolution from one level to another requires that spatial parameters have to be clearly identified in each model. After selecting the characterization models, these had to be adapted to the Canadian conditions. This means that data had to be gathered or, in more difficult cases, changes had to be made to the model when required data was not available for Canada.

1.3 How do models integrate site-specificity?

Ideally, characterization models should include site-specificity in both effect and fate factors of local and regional impacts (Eq. 1).

Characterization Factor = Effect Factor. Fate Factor (1)

Very few characterization models integrate site-specificity for both these factors: Huijbregts et al. (2000) made early attempts for acidification and eutrophication; EDIP2003's models for acidification and eutrophication (using the RAINS model) (Hauschild et al. 2003) and LIME's acidification model (Hayashi et al. 2004) have successfully integrated site-specificity.

Most models only integrate spatial considerations in the fate factor as does IMPACT 2002+ for ecotoxicity and toxicity (Jolliet et al. 2003) and TRACI for acidification and eutrophication (Norris 2003). Fate contaminants largely depend on the environmental conditions, for instance, SO_2 and NO_x deposition will depend on atmospheric transport, eutrophying substance fate will depend on groundwater characteristics, toxic substances will depend on environmental transport, exposure and the resulting intake.

It can appear easier to integrate site-specificity into effect factors, since they are not based on sophisticated transport models but on measurable receptors that account for environmental characteristics such as population composition, state of receptors, critical loads, geographic, physical and chemical features, which are easier to measure. However, because these data are very site-specific, characterization models do not generally integrate them. To integrate site-specificities in effect modelization, other regional specific factors can also be used. For instance, regional scaling factors (Tolle 1997) are numerical scores used to indicate ranges in the degree of sensitivity which a particular region has for the selected impact category. According to Tolle (1997), these factors allow the improvement of accuracy in generic characterization factors. Sensitivity is represented by background level concentrations such as critical loads for acidification. Huijbregts et al. (2000) also used critical loads for acidification and eutrophication effect characterization models through the use of the RAINS model. In the context of nitrogen emission management, Meinardi et al. (1995) developed equations to assess topsoil and groundwater vulnerability to diffuse pollution (Eq. 2 and 3 in **Table 3**). While these factors improve the assessment of potential hazard overall, they do not evaluate site-specific impacts. Despite their simple use and scientific relevance, these equations have never been used in an LCIA context until now.

LUCAS has integrated site-specificity in regional impacts for the effect modelization of acidification and eutrophication (aquatic and terrestrial) with vulnerability factors developed by Meinardi et al. (1995) (see Table 3). The vulnerability of the soil to diffuse pollution depends on land cover, topsoil features, net precipitation, aquifer type, groundwater recharge and age and can be expressed as shown in equation (2) in Table 3. Vulnerability of the groundwater to diffuse pollution depends on soil vulnerability, aquifer type, thickness of the unsaturated zone and groundwater age (equation 3 in Table 3). Details on the ranking of vulnerability classes and weighting factors are presented in Meinardi et al. (1995).

Vulnerability factors could not be used for local impact categories since they refer to soil and groundwater sensitivity instead of biological receptor sensitivity.

1.4 Spatial resolution

Hauschild et al. (2003) have specified different levels of spatial resolution: generic, site-dependent and site-specific. An example of a site-generic method is EDIP97, where no spatial differentiation is performed in source and receptor environments. Site-dependent and site-specific modelling differs by the degree of detail in the resolution. While site-depend-

Table 3: Vulnerability factors for the different regional impact categories in LUCAS (where W_a, W_b, W_c: weight factors; R_a, R_b, R_c: specific risk of contamination related to land cover, net precipitation and topsoil texture; W_a, W_b, W_c: weight factors; R_d: vulnerability of topsoil; R_f: aquifer type; R_e: thickness of the unsaturated zone; R_g: groundwater age)

Impact categories	Regionalization	Vulnerability factors
Acidification	Vulnerability for soil pollution + critical loads values	Vulnerability of soils (Rd) = $W_a*R_a + W_b*R_b + W_c*R_c$ (2)
Aquatic eutrophication	Vulnerability for groundwater pollution	Vulnerability of groundwaters = $W_d*R_d + W_e*R_e + W_f*R_f + W_g*R_g$ (3)
Terrestrial eutrophication	Vulnerability for soil pollution	Rd

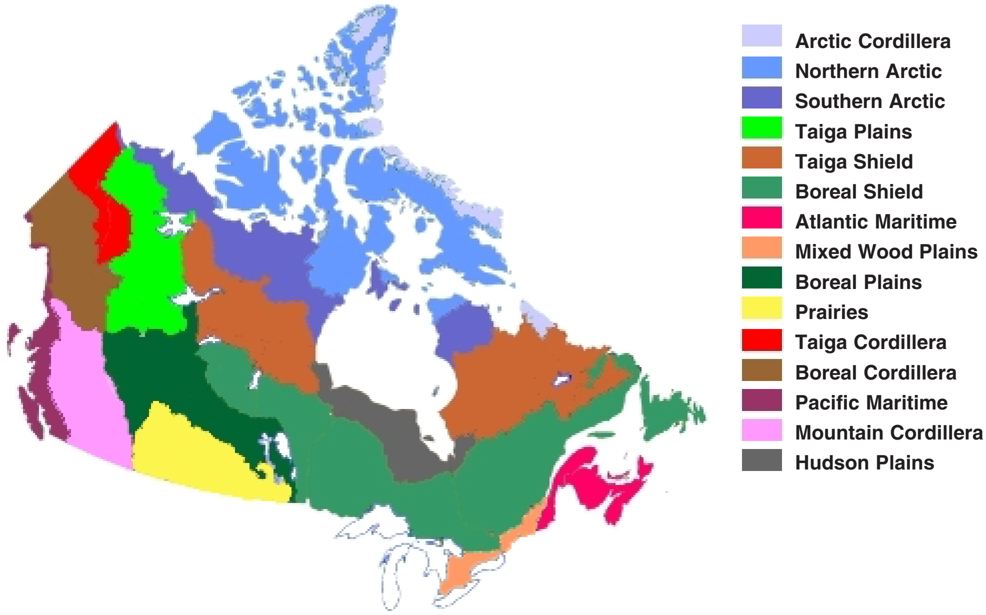

Fig. 1: The 15 Canadian terrestrial ecozones (adapted from Statistics Canada 2004)

ency concerns large areas such as countries or regions (IMPACT 2002+, EDIP2003, TRACI), site-specificity involves models that consider sources at specific locations (Hauschild et al. 2003). Site-dependency is the level of spatial differentiation that is suggested for characterization modelling in EDIP2003, since it is the one which has the best chance of offering readily available data (Hauschild et al. 2003). Site-dependency was chosen for LUCAS and the 15 Canadian ecozones were selected as the spatial resolution unit (**Fig. 1**). This ecological cartography devising the territory into 15 terrestrial zones was established under a Canadian government initiative (Wiken 1986). Each ecozone has its own climate, relief, soil, fauna, flora and distinct human activities. For example, the Prairies' ecozone contains more than 60% of Canada's cropland and 80% of rangeland and pasture (Wiken 1986), while the Boreal Shield is covered by forests on 80% of its area and agriculture is limited to a few areas of fertile soil.

Terrestrial ecozones have been chosen as the spatial resolution scale unit for the following reasons:

- their ecosystem relevance and values;
- the required data for models are available for each ecozone: Environment Canada has provided a complete database on various geographical features used in impact assessment models (Marshal and Schut 1999). Transformation of data based on surface area proportions was performed only when province data were available instead of ecozone data;
- their large area facilitates the accessibility to site-dependent inventory data. The ecozone surface areas range from 168,000 km^2 (mixed wood plains) to 1,940,000 km^2 (boreal shield). Concern with inventory compatibility with the spatial resolution selected lead us to choose this large resolution unit. Another concern associated with using an average characterization factor for the entire ecozone is that it can have wide variations in sensitivity to a particular impact category. However, some inventory data are very difficult to obtain for portions of an ecozone, so a more precise land area resolution of the characterization factor would not be helpful;
- this level of geographical hierarchy has already been largely used and will, therefore, facilitate communication at industrial and governmental levels.

1.5 Normalization

The same normalization method as in IMPACT 2002+ has been used and can be summed up by Eq. 4:

Normalization Factor =
Total impact of annual emission in the ecozone / (4)
Population of the ecozone

The normalized factor is determined by the ratio of the impact per unit of emission divided by the total impact of all substances contributing to the specific impact category, per person, per year (Jolliet et al. 2003). Required data for populations and emissions were provided by Statistics Canada (2004) and Environment Canada (2002). Considering the high number of substances characterized in IMPACT 2002+ for ecotoxicity and toxicity, the normalization factors were calculated with only the priority substances established by Environment Canada (1999).

2 Characterization Model Adaptation

Ten impact categories were characterized in LUCAS. For global impacts (climate change, ozone depletion, abiotic resource depletion), models were used exactly as presented in

Table 4: Main aspects of LUCAS' site-specific characterization models

Impact Category	Category indicator	LUCAS specificity compared to the original model
Acidification	Potential proton release (H^+ equivalents)	– ASTRAP outputs transformed in ecozone data; regionalization of effect with vulnerability factors – Vulnerability factors
Photochemical smog	Maximum Incremental Reactivity (MIR)	ASTRAP outputs transformed in ecozone data
Aquatic eutrophication	Marginal load variation caused by a 1 kg increase in loading of N (or P)	– Model simplification, because ecozones were not simplified – Vulnerability factors
Terrestrial eutrophication	Amount of atmospheric nitrogen that contributes to terrestrial eutrophication	– Model to take into account only the nitrogen available to terrestrial eutrophication in Canadian forests. – Vulnerability factors
Ecotoxicity	Marginal risk-based factors expressed in terms of PAF (PDF) and the area of surface affected (kg eq triethylene glycol)	None
Toxicity	Marginal change in cumulative population based risk and potential impact expressed in DALY (kg eq chloroethylene)	None
Land-use	Biodiversity and LSF (Life Support Functions)	Ecozone data instead of biome data

other LCIA methods. For regional and local impacts, some models were modified with Canadian data (acidification, smog formation, ecotoxicity, toxicity, land-use) and improved with vulnerability factors (acidification, aquatic and terrestrial eutrophication). For aquatic and terrestrial eutrophication, calculation procedures were adapted and transformed according to data availability. **Table 4** presents the indicators and adaptations used for the site-dependent impact categories.

For each ecozone, 2334 site-dependent characterization factors are available (6 for acidification, 510 for smog formation, 5 for aquatic eutrophication, 1 for terrestrial eutrophication, 1023 for ecotoxicity, 781 for toxicity and 2 for land-use). Ecozone data which were used in calculation models were provided by national organizations such as Statistics Canada (2004) and Environment Canada (2002).

2.1 Climate change and ozone depletion

Global warming and ozone depletion characterization models are internationally accepted and are the same in any LCIA method. These characterization factors are supported respectively by the International Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO). Characterization factor values for these two impact categories were provided by the EDIP2003 technical report (Hauschild et al. 2003).

2.2 Acidification, photochemical smog, aquatic and terrestrial eutrophication

TRACI's acidification and photochemical smog characterization models were selected for LUCAS based on their level of sophistication and the fact they could be adapted to the Canadian geographical context (see Table 3).

For aquatic eutrophication, since TRACI data were not available for any of the ecozones, the EDIP2003 marginal characterization model was selected, simplified and adapted to the 15 Canadian ecozones. Terrestrial eutrophication remains a complex impact category with no consensus on which indicators should be used (Potting et al. 2002). It covers adverse effects of excess nutrients on plant function and on species composition in natural or semi-natural terrestrial ecosystems. The atmospheric input of nitrogen caused by human activity contributes considerably to an excess of nutrients. It was decided, for now, to select the simplest category indicator developed by Lindfors et al. (1995): the amount of atmospheric nitrogen emitted to air which reaches a natural ecosystem. This indicator indicates the potential increased biomass production in terrestrial ecosystems (Lindfors et al. 1995). In LUCAS, only natural ecosystems such as forest areas were considered for terrestrial eutrophication.

2.2.1 Regionalized fate

Acidification and Photochemical Smog. LUCAS uses ASTRAP (Advanced Statistical Trajectory Regional Air Pollution), a North-American deposition model, to assess SO_2 and NO_X fate in acidification, photochemical smog and eutrophication (aquatic and terrestrial). The ASTRAP model provides matrices repartition for SO_2 and NOx for the 10 Canadian provinces. Provincial data were transformed into ecozone data according to area proportions. Outputs from ASTRAP (SO_2 and NO_x deposition matrices) were used to assess the fate in acidification and photochemical smog with the same calculation procedure as that developed by Norris (2003) for TRACI. For photochemical smog, Norris assumptions allowed to assess VOC fate from NOx fate and also to assess O_3 concentrations per province.

Aquatic and Terrestrial Eutrophication. In the aquatic eutrophication category, nitrogen is provided by agriculture (manure and fertilizers), wastewaters and atmospheric deposition. Once again, the ASTRAP model was used for atmospheric nitrogen fate. Nutrient loading (L) by point (wastewater) and non-point sources (agriculture from manure and fertilizers) and phosphorus loading from agriculture were

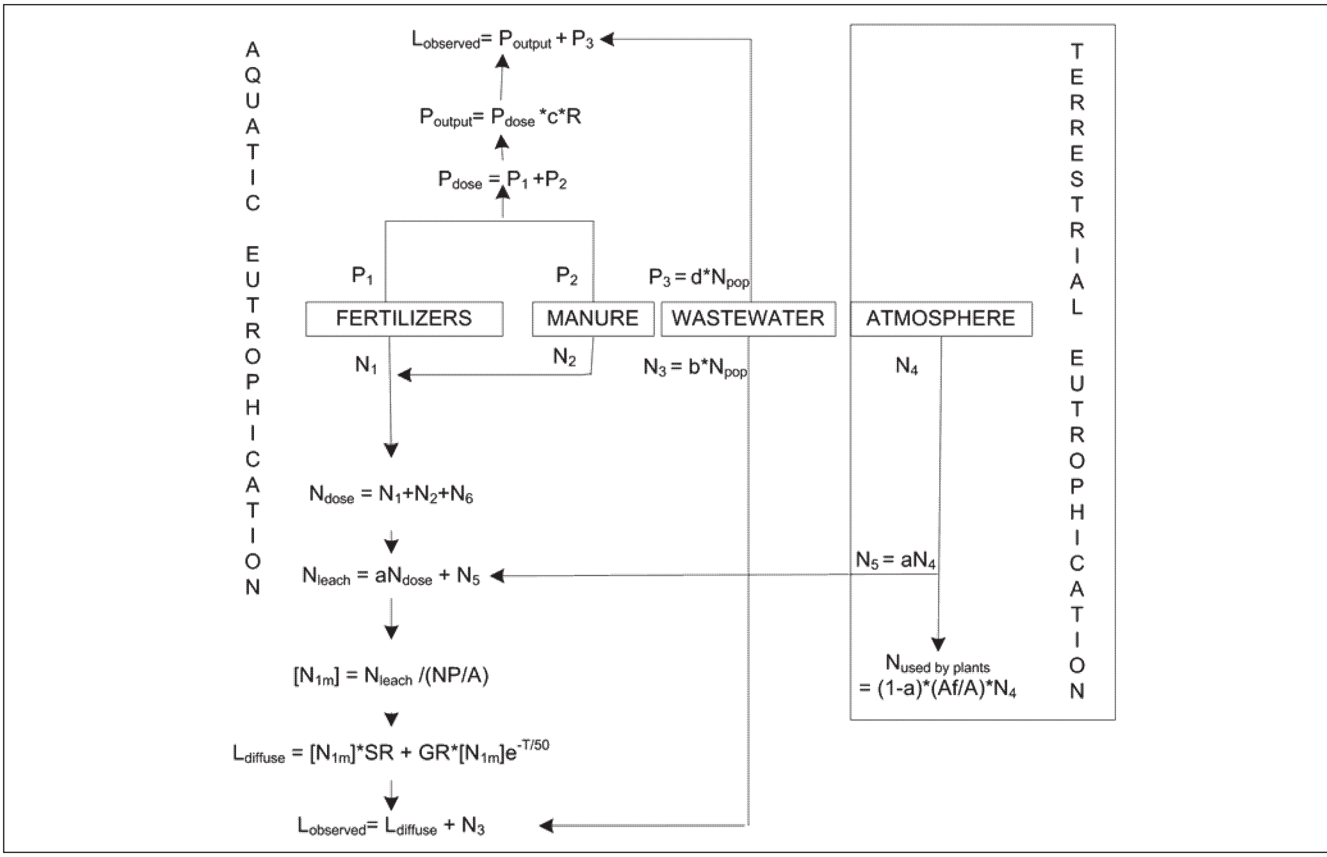

Fig. 2: Calculation procedures for aquatic and terrestrial eutrophication for N and P (where a: lixiviation factor to relate applied dose (N_{dose}) and leached amounts (N_{leach}); A: area of each ecozone; N_{pop}: population in the ecozone; NP: net precipitation; SR: surficial runoff; GR: groundwater recharge; T: aquifer age; N_1, P_1: quantity of nitrogen/phosphorus from fertilizers; N_2, P_2: quantity of nitrogen/phosphorus from manure; N_3, P_3: quantity of nitrogen/phosphorus from wastewaters; N_4: quantity of atmospheric nitrogen received (outputs from ASTRAP model); R: erosion rate; Af: forest area in each ecozone, b = 9.2 gN.inh^{-1}.day^{-1} ; c = 1.18.10^{-4} (tsoil.tP)$^{-1}$km^{-2}yr^{-1}; d = 2.12 gP.inhab^{-1}.day^{-1}), $L_{diffuse}$: diffused nutrient load; $L_{observed}$: observed nutrient load)

assessed thanks to the CARMEN (CAuse effect Relation Model for Environment policy Negotiations) model (**Fig. 2**) (Haan et al. 1996). CARMEN model assesses wastewater and agriculture inputs using parameters such as soil erosion rate, groundwater depth and population in the region (see Fig. 2). The total discharge of nitrogen and phosphorus is calculated by combining land-based (atmospheric and agricultural) and population-based (wastewater) inputs per region. The model for the diffuse sources and nitrogen pathways, results in a load of nitrate to surface waters (see Fig. 2). CARMEN requires the estimation of few parameters which include the loss rate due to denitrification and the proportionality of inhabitants to sewage inputs (**Table 5**). In order to take into account the missing ammonia and organic fractions in the model, the diffuse source ($L_{diffuse}$ in Fig. 2) is multiplied by the proportionality factor 0.7 (ammonia and organic nitrogen represent approximately 30 % of total nitrogen) (Klepper et al. 1995). The population of each ecozone was used to assess the amount of nitrogen from wastewater. The model calculates N-input from wastewater as propor-

Table 5: Site-specific parameters required for N and P input assessment for aquatic and terrestrial eutrophication

	Parameters	Characterization Factors= $L_{obs+1} - L_{obs}$	(5)
N agriculture	– N inputs – Aquifer type – Soil texture – Slope – Land-use – Temperature – N_{pop} – ASTRAP outputs	$CF_{agriculture} = [0.7a(SR+GRe^{-T/50}]/(NP*A)\ ((N_1+N_2+1)+N_5) - ((N_1+N_2+1)+N_5)$	(6)
N wastewater		$CF_{ww} = 0.7*\ [L_{diff} + N_3+1] - 0.7*\ [L_{diff} + b*N_{pop}]$	(7)
N atmospheric		$CF_{atmo} = [0.7a(SR+GRe^{-T/50}]/(NP*A)\ (N_1+N_2+(N_4+1)) - (N_1+N_2+(N_4+1))$	(8)
P agriculture	– P inputs – N_{pop} – Erosion rate R	$CF_{agriculture} = (d*N_{pop} + c*RP_{input}+1) - (d*N_{pop} + c*RP_{input}+1)$	(9)
P wastewater		$CF_{ww} = (d*N_{pop} + 1 + c*RP_{input}) - (d*N_{pop} + c*RP_{input})$	(10)
N terrestrial	– ASTRAP outputs	$CF_{terretrial\ eutro} = (1-a)N_4$	(11)

tional to population density. The 9.2 g $N.inh^{-1}.day^{-1}$ (b in Fig. 2) factor has been obtained from an empirical calibration performed with European data (Klepper et al. 1995). For more details on the assumptions considered in CARMEN, see Klepper et al. (1995).

For terrestrial eutrophication, only the quantity of atmospheric nitrogen that did not contribute to aquatic eutrophication was considered (see Fig. 2). As for the acidification and photochemical smog impact categories, atmospheric N was also assessed with NOx ASTRAP matrices outputs for terrestrial eutrophication. These outputs from ASTRAP were allocated as a function of each ecozone forest area (considered as the only ecosystem affected by terrestrial eutrophication).

2.2.2 Effect

Acidification and Photochemical Smog. Acidification potentials were assessed based on the transformation of NOx and SO_2 concentrations into moles of H^+ equivalents as done in TRACI (Norris 2003). These effect factors were regionalized through the use of vulnerability factors which were multiplied by the repartition matrices (see Table 3). Aside from vulnerability factors, acidification characterization factors can be regionalized by taking into account soil critical loads. Based on regional scaling factors (Tolle 1997), it has been decided to include critical loads to reflect sensitivity levels to acidification. Hence, maps of acid-sensitive soils were used and values of critical loads were multiplied by vulnerability factors.

For photochemical smog, Maximum Incremental Reactivity (MIR) has been developed by Carter (2003) based on US data. MIRs are not intended to represent any particular region, just urban areas in general and were therefore used as generic effect factors in LUCAS. No effect regionalization was performed for the photochemical smog formation category in LUCAS. Integrating data such as background ozone concentrations in each ecozone would have incorporated too many uncertainties due to the difference in scale between smog data and ecozone data.

Aquatic and Terrestrial Eutrophication. Similarly to EDIP2003's approach for aquatic eutrophication, LUCAS' model is based on a marginal approach since the CARMEN model calculates the change in nutrient loads in groundwater and inland waters from changes in nutrient inputs (Hauschild et al. 2003) (Eq. 5).

$$CF = L_{obs+1} - L_{obs} \quad (5)$$

Where

L_{obs}: Nutrient loading obtained from CARMEN model calculations

L_{obs+1}: Nutrient loading caused by the change in the total amount of either nitrogen or phosphorus from a given source category (atmospheric, agriculture or wastewater)

Aquatic eutrophication can be caused by nitrogen or phosphorus:

Nitrogen. Each source has its own characterization factors since, depending on its origin, nitrogen will not have the same fate and effect (see Fig. 2). Characterization factors are calculated by changing the total amount by 1 kg of nitrogen from a given source category in one ecozone as EDIP2003 does with each river catchment (Hauschild et al. 2003). EDIP2003 accumulates the 1 kg loading increase over all river catchments for one country then integrates these marginal results in the different RAINS zones for each country (Hauschild et al. 2003). Since there is no sub-division of ecozones in LUCAS, characterization factors take only into account the N-input increases in each zone. This marginal approach will be improved as soon as a model that provides nitrogen and phosphorus-specific fate models for Canadian watersheds is made available.

The atmospheric transport from emission to deposition is implemented in CARMEN by means of ASTRAP source-receptor matrices. In this particular case, in order to follow the EDIP2003 marginal approach, the emission was increased by 1 kg and results on deposition were noted (for manure and fertilizer, emission equals deposition).

Phosphorus. According to CARMEN methodology, characterization factors for phosphorus are provided by equations 9 and 10 in Table 5 (Klepper et al. 1995). As for nitrogen, coefficients used in equations 12 to 15 ($c = 1.18.10^{-4}$ ($tsoil.tP^{-1}km^{-2}yr^{-1}$) and $d = 2.12$ $gP.inhab^{-1}.day^{-1}$) were obtained from linear regression of calculated on observed loads (Klepper et al. 1995).

For aquatic eutrophication, regionalization was integrated with the use of vulnerability factors for groundwater. These vulnerability factors were multiplied by the quantity of nitrogen that contributes to aquatic eutrophication (prior to applying the marginal calculations).

Since no current consensus prevails yet on an appropriate terrestrial eutrophication indicator, the authors have chosen, for now, to consider only the amount of atmospheric nitrogen that does not contribute to aquatic eutrophication (see Fig. 2, Eq. 11 in Table 5). This nitrogen amount was then multiplied by a soil vulnerability factor.

2.3 Ecotoxicity/Toxicity

To assess the impact on ecotoxicity and human toxicity, the IMPACT 2002 (Pennington et al. 2005, 2003) tool which models cumulative risks and potential impacts per emission was adapted to the Canadian context. This tool used within the complete IMPACT 2002+ (Jolliet et al. 2003) LCIA methodology proposes a combined midpoint and damage oriented approach, including environmental fate, exposure and effect of chemicals. Spatial distinctions were made only at the levels of chemical transport and environmental exposure, not on the effect. IMPACT 2002 was selected among other LCIA approaches for toxicological impacts according to several reasons, but mainly because this model is adapted to the comparative nature of LCA. Indeed, IMPACT 2002 estimated cumulative risks integrated over time and space which differs from LCIA methodologies based on conservative regulatory approaches.

2.3.1 Fate

IMPACT 2002 was selected among other fate models because of its environmental relevance and modeling improvement. IMPACT 2002 fate calculations include a transformation model as well as spatial and multimedia transports. The air modeling was improved thanks to the adjustment of the intermittent character of rain in a steady-state model; the assumption of continuous rainfall could lead to an underestimation of the air concentrations (Hertwich 2001). For human health impact assessment, multiple intakes were considered such as inhalation, drinking water ingestion, accidental soil ingestion, intake of agricultural products and animal products. The calculation of the intake dose through food is not based on consumption surveys like the traditional approach, but accounts for the production that will eventually be ingested by humans independently of their living location (Jolliet et al. 2003). This approach is suitable for comparison purposes and limits the uncertainties associated with the estimation of export and import of food. For ecotoxicity, the interface between fate and effect is at the level of concentration, since the exposure is generally implicitly taken into account in the effect factor (Jolliet et al. 2003). For each module in IMPACT 2002 (soil, fresh water, sediment, oceanic water, air, vegetation), all physical (e.g. rainfall rate), geographical (e.g. sediments area), exposure (e.g. human population) and usable production (e.g. annual production of beef for human consumption) parameters were adapted to each Canadian ecozone.

2.3.2 Effect

IMPACT 2002 proposes new approaches for the assessment of effect factors. For human toxicity, chronic effects associated with carcinogenic and non-carcinogenic substances are characterized using a benchmark dose resulting in 10% effect over background as detailed in Crettaz et al. (2002) and Pennington et al. (2002). The AMI (Assessment of the Mean Impact) method developed by Payet and Jolliet (2003) was selected for the assessment of the ecotoxicity effect factors. This method estimates the change in the Potentially Affected Fraction (PAF) of species that experience an increase in stress due to a change in exposure. The geometric mean of available EC_{50}s is the basis for the calculations. In addition, the method provided the assessment of uncertainties associated with the effect factor. As detailed in Payet and Jolliet (2004), this median approach allows avoiding an unintentional bias. The conservative approach is sensitive to the species tested resulting in great variations between databases. Also, the effect factor of a toxic chemical can be developed with just a few data. Data availability is an important issue, since a large number of chemicals are generally treated in an LCI and some characterization factors for chemicals are generally missing and need to be developed. The calculation of ecotoxicity accounts for the volume of water or soil affected which is realistic since polluting a small portion of the lake versus the entire lake to the same level of risk is not considered to be equivalent (Pennington et al. 2004).

2.4 Land-use

The model selected in LUCAS for land-use is based on work by Weidema et al. (2001) and has been selected since it takes into account both impacts related to biodiversity and those related to life support functions (LSF). The indicator for biodiversity is given by equation 12:

$$Q_{biodiversity} = nSR.\ nES.\ nEV \quad (12)$$

Where

SR: Species richness of the ecosystem (or number of species by surface area)
ES: Inherent ecosystem scarcity
EV: Ecosystem vulnerability
n: Normalization factors

Vascular plants are used as proxy for species richness. Inherent ecosystem scarcity is expressed as the inverse of the potential area that could be occupied by the ecosystem if left undisturbed by human activities. Ecosystem vulnerability is linked to the stress level the studied ecosystem already has to cope with; it indicates the relative number of species affected by a change in the ecosystem area, as expressed by the species-area relationship. Net Primary Production (NPP), which is defined as the net carbon uptake of the ecosystem (fixation through photosynthesis minus losses through respiration) over time, is the indicator for the LSF of natural systems. The LCAGAPS report (Weidema et al. 2001) provides characterization factors for world biomes. Using the same calculation process, characterization factors for each of the 15 terrestrial Canadian ecozones were calculated; when ecozone data were not available, biome data were used in the calculation procedures. For more details on this model, see Weidema et al. (2001).

2.5 Resources

The characterization model selected for resources was the one used in Eco-indicator 99 for mineral resources and fossil fuel. All details concerning this model can be found in a Pré Consultant report (Goedkoop et al. 2001). Aside from Eco-Indicator 99, this model is used by both the TRACI and IMPACT 2002+ methods. This model is based on the assumption that continued extraction and production of fossil fuels tends to consume the most economically recoverable reserves first; then, in the future, continued extraction will become more energy demanding. Scenarios for replacement fuels (for each fuel type) were generated by considering a point in the future at which the total cumulative consumption would represent five times that of the present consumption (Bare et al. 2003). The same approach was used for mineral resources.

3 Discussion

LUCAS provides characterization factors for the 15 Canadian terrestrial ecozones. The main advantage of this methodology is its transparency and the ease with which it allows the calculation of new characterization factors for other spatial resolution scales. LUCAS selected the same model as TRACI for regional transboundary impact categories (acidification, photochemical smog). This choice is logical since Canada and the United Sates share similar regulations for atmospheric pollution. Integrating site-dependent parameters in the characterization factor calculation procedure was a main concern for LUCAS developers. ASTRAP and CARMEN models allowed one to modelize fate of regional impacts while taking into account the Canadian geographical context. The CARMEN model appeared to be a very appropriate integrated assessment model for eutrophication characterization models.

This is the first time that the vulnerability factors developed by Meinardi et al. (1995) have been used in LCIA. These factors were calculated for each ecozone; they summarized the situation of the topsoil and groundwater in relatively large areas, thus ignoring much of the local detail. Moreover, the use of ASTRAP allowed taking into consideration both places of emissions and reception thanks to SO_2 and NOx deposition matrices. LUCAS has the main advantage of being easily adaptable to smaller or larger regions if necessary. Models have been selected as a function of the calculations and data required. This creates the need for further improvements in this methodology:

- Regionalization of the effect remains a simplification; an appropriate site-specific effect model such as the one used in EDIP2003 for regional impacts would be more accurate. EDIP2003 used RAINS to establish patterns of deposition and concentration (Hauschild et al. 2003). While RAINS can compare actual concentrations with critical loads and thresholds, outputs from ASTRAP are only source-receptor matrices, as in LUCAS, and as such, relate emissions by source area to deposition per hectare in a grid of receiving areas (Norris 2003), which means that effect is not directly included. An adaptation of the method to attain a more specific representation of the vulnerability for a type of pollutant will be investigated.
- For the aquatic eutrophication category, the eutrophication state of lakes was not taken into account nor was any hydrological modelization in each ecozone. The TRACI model, however, did use such a complex hydrological modelization for the fate of underground and surface waters. Unfortunately, such data could not be found for the spatial resolution chosen in LUCAS. As soon as data for all Canadian watersheds is made available for this LCIA model, the marginal approach used for aquatic eutrophication will significantly be improved (with an integration of watersheds for each ecozone). An additional future improvement to aquatic eutrophication modelization is the differentiation between saline and freshwater with the consideration of the 5 marine Canadian ecozones. These additional ecozones could also be considered for aquatic ecotoxicity.

For terrestrial eutrophication, the model needs to be improved since there is no real impact indicator; the model only assesses the amount of nitrogen entitled to air since it indicates the increased biomass production in terrestrial ecosystems. A more sophisticated indicator such as the one used in EDIP2003, which is the change in the area of ecosystems above critical load from a marginal change, should be investigated.

The spatial version of IMPACT 2002 would have provided a more accurate assessment than the a-spatial version. The use of the IMPACT 2002 spatial version (Pennington et al. 2005, 2003) is presently considered for further development.

4 Conclusion and Outlook

The LUCAS LCIA methodology proposes an attractive and useful set of site-dependant characterization factors for the 15 Canadian terrestrial ecozones. Several limitations must be noted, however: several impact categories have not been considered thus far, including water consumption and noise. Efforts are also carried out to extend the specificity of some factors used in eutrophication modelization. Further developments in the LUCAS methodology include the integration of regionalization in ecotoxicity and toxicity fate model, the addition of uncertainties (on data and models) in characterization factors and an aggregation method. For now, this Canadian methodology consists of adaptations from existing LCIA models. On-going research on acidification and eutrophication characterization models will allow further improvements of the models. The transparency of the methodology will allow stakeholders to recalculate site-dependant characterization factors for different regions and additional substances depending on the goal and scope of the LCA study.

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