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Method for considering life cycle thinking and watershed vulnerability analysis in the environmental performance evaluation of agro-industrial innovations (Ambitec-Life Cycle)

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Abstract

The current emphasis on sustainable development warrants the development and adoption of innovations to render industrial production more efficient in the use of natural resources and less polluting. In order to develop innovations for sustainability, management models and evaluation tools must integrate objective environmental considerations. One such tool is the Ambitec-Agro System, a set of integrated indicators specifically proposed to assess environmental impacts of agro-industrial innovations. This System compares an innovation's environmental performance against the pre-existing technology, focusing the analysis on the innovation-adopting establishment scale. This study presents a conceptual method that expands the scope of Ambitec-Agro by including life cycle thinking and watershed vulnerability analysis to the environmental performance evaluation of agro-industrial innovations. In order to develop this approach, the steps inherent to a multi-criteria decision support system were followed. The proposed method includes four life cycle phases to evaluate the environmental performance of an agro-industrial innovation: (i) raw material production used by innovation, (ii) innovation production, (iii) innovation use and (iv) its final disposal. The method also includes a vulnerability analysis of the watersheds where each life cycle phase takes place. The proposed integrated method provides decision makers a broadened view of an agro-industrial innovation environmental performance, shedding light on technological improvements throughout its entire life cycle.

Introduction

According to the World Business Council for Sustainable Development (WBCSD), environmental sustainability requires the development of innovations that contribute to the efficient use of natural resources (WBCSD, 2001). In consonance with this directive, the Ambitec-Agro System (Rodrigues *et al*., 2003) has been used since 2001 to assess the environmental impacts of agro-industrial innovations proposed by research and development (R&D) programs carried out at the Brazilian Agricultural Research Agency (Embrapa). This System integrates environmental impact indicators in weighing matrices designed to compare the performance of a given innovation with the performance of a previously existing technology, focusing the analysis on the productive unit (the rural establishment or agroindustry) where the innovation is adopted (Monteiro & Rodrigues, 2006).

However, during the last decade, the scientific community witnessed the intensification of the debate about the importance of evaluating the impacts of products or services along their production, consumption and post-consumption phases, that is, along their life cycle. The Society of Environmental Chemistry and Toxicology (SETAC) and other institutions have sponsored workshops and projects to develop a conceptual framework for conducting life cycle assessments (LCA). This framework is formally presented in the ISO 14040 and 14044 standards (Roy *et al*., 2009).

LCA of agro-industrial products is spreading with the development of impact assessment methods that consider emissions from the use of agrochemicals and their impacts on the environment (Roy *et al*., 2009; Nemecek *et al*., 2008). However, some difficulties still contribute to the restricted use of LCA in certain countries such as Brazil: the scarcity of locally detailed databases to support data inventories, despite recent efforts such as the first Brazilian database on energy production in 2007 (Ferreira *et al*., 2007); the lack of consolidated methods to evaluate impacts on soil, such as erosion, salinization and compaction, and impacts on water availability, all issues of special interest to the Brazilian context, especially in semi-arid areas (Pennington *et al*., 2004; Pegoraro, 2007).

The consideration of the environmental vulnerability of a natural system that receives emissions released in a life cycle phase is also important, since each system is affected differently depending on its socioeconomic and environmental characteristics. Although the vulnerability concept is not consensual in scientific terms, according to Adger (2006), it is usually linked to one or more of the following factors: exposure, system's sensitivity and adaptive capacity. Exposure means the level, duration or extension of the system contact with perturbations. Sensitivity is related to the system's ecological capacity to assimilate environmental pressures without being degraded in the long run. System's adaptive capacity concerns the ability to make use of resources or respond to pressures, preventing, controlling or remediating environmental degradation. The quantification of these factors allows the evaluation of a system's vulnerability to specific environmental pressures, with a system being more vulnerable when exposure and sensitivity are high and adaptive response is low.

The LCA framework according with ISO 14040 does not considerer a system vulnerability to consumptions and emissions related to a studied product life cycle. Nonetheless, some life cycle impact assessment methods such as EDIP (Potting & Hauschild, 2005) and TRACI (Bare *et al*., 2003) developed site-dependent characterization factors to consider spatial differentiation in some impact categories, at a regional level. The consideration of the characteristics of the surrounding environment is especially important in the impact assessment of agricultural activities.

This study presents a conceptual method named Ambitec-Life Cycle that considers life cycle reasoning and watershed vulnerability analysis in the environmental performance evaluation of agro-industrial technological innovations. The proposed method aims to subsidize agro-industrial innovations' R&D, showing critical points in an innovation life cycle that need to be addressed to innovations reach better environmental performance than its substitute technology. This method is based on and expands the scope of the Ambitec-Agro System.

Method

In order to develop Ambitec-Life Cycle, the steps described below were followed, as proposed by Malczewski (1999) for the delineation of a multi-criteria decision support system:

(i) Definition of the decision question to be addressed: the decision question is: how to expand the Ambitec-Agro System to consider different phases of an innovation's life cycle and the vulnerability of the environment where each phase of its life cycle occurs?

To answer this question, it is necessary to make it clear what is understood by life cycle and vulnerability. The life cycle concept adopted is present in the ISO 14040 standards: life cycle is related to successive and connected stages of a production system, from raw material acquisition to product final disposal. The vulnerability concept adopted is based on Adger (2006), applied to the watershed scale and encompasses: exposure to human pressures that have the potential to cause environmental impacts; sensitivity of the ecological system to the pressures; and local society capacity of response to the environmental pressures.

The following environmental impacts were pointed out as relevant to the study of agro-industrial activities: (i) loss of biodiversity, (ii) soil erosion, (iii) compaction, (iv) salinization, (v) sodification, (vi) acidification, (vii) desertification, (viii) environmental contamination by agrochemicals and (ix) solid wastes, (x) water scarcity and (xi) pollution, (xii) depletion of non-renewable resources, (xiii) climate change and (xiv) food contamination by use of additives (Figueirêdo, 2008).

ii) Identification of possibilities to apply the multi-criteria analysis: as in the Ambitec-Agro System, the analysis is applied to two technologies - the focused innovation and a substitute technology already being used with a similar function in the market. By comparing the environmental performance of an innovation with the performance of its substitute technology, it is possible to identify whether the innovation causes more or less impact than its substitute technology and to proceed with changes and improvements in the innovation characteristics, if necessary.

iii) Definition and organization of indicators and indices: the hierarchical multi-criteria structure of the Ambitec-Agro System (Rodrigues *et al*., 2003) was expanded to consider other life cycle phases of the studied innovation and its substitute technology. This multi-criteria structure organizes environmental indicators in principles and criteria, aggregated as an environmental performance index.

To perform the vulnerability analysis, a multi-criteria structure that organizes indicators in criteria and in a watershed vulnerability index was also developed.

iv) Definition of rules to the multi-criteria analysis: the rules established standards to process data in the proposed method and were based on the multi-criteria theory revised by Malczewski (1999).

v) Sensitivity analysis: with the quantitative methods in place, simulations were performed with each indicator assuming variations (±10%, ±50%, change to zero and change from zero to a greater number), in order to measure the sensitivity of the method, as proposed by Jorgensen (1994).

Results

The conceptual method of Ambitec-Life Cycle and the main steps necessary to its implementation are shown in Fig. 1. Four life cycle phases are considered for a given innovation, instead of just the use phase as in the scope of the original Ambitec-Agro System: raw material production used by the innovation, innovation production, innovation product use and its final disposal.

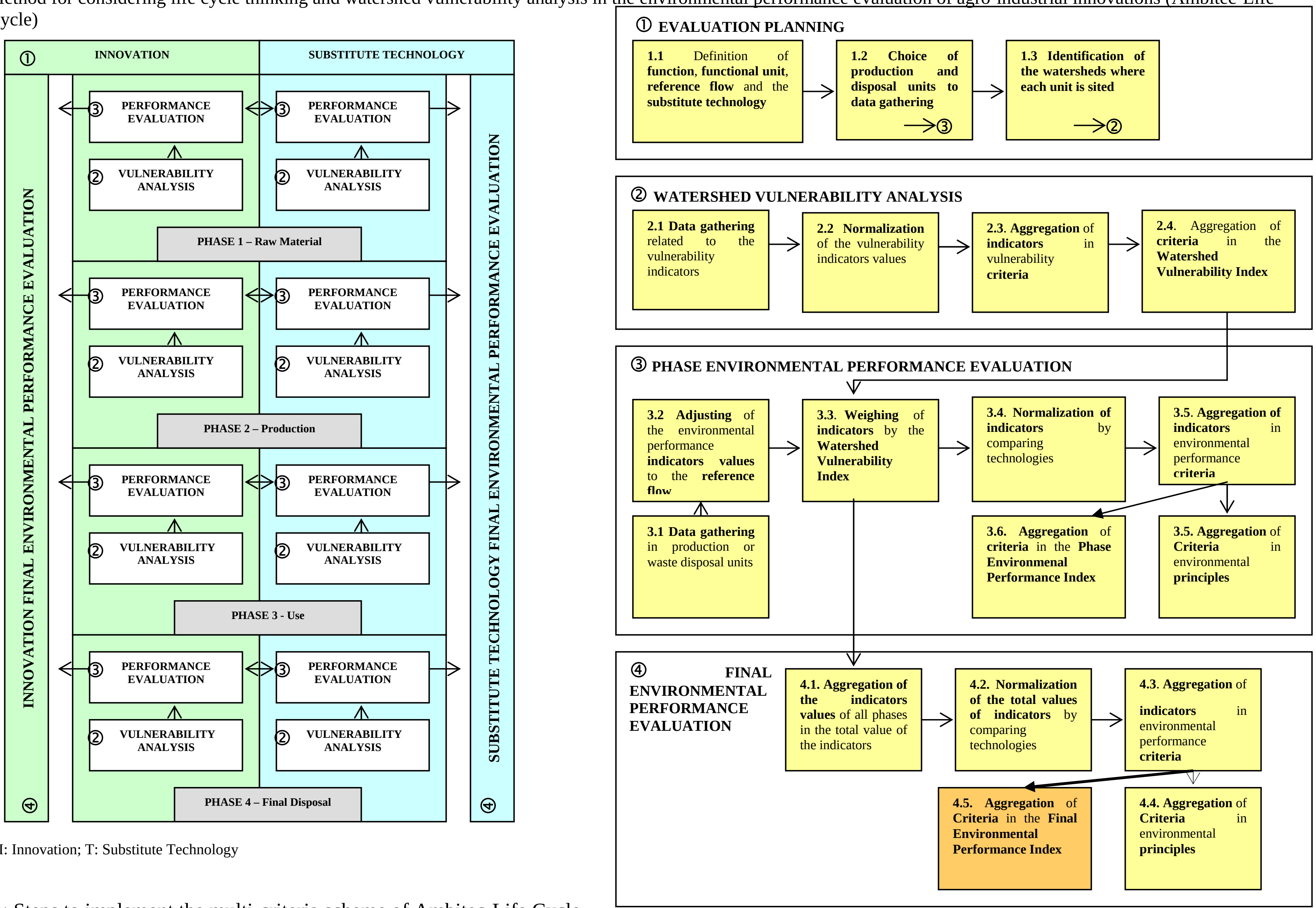
If an innovation uses a byproduct or residue as a raw material, the first phase is not considered. However, if the use of such an innovation leads to the disposal of byproducts or residues formerly used by its substitute technology, this disposal must be accounted for in the raw-material phase.

The environmental performance analysis along these life cycle phases must be carried out to an innovation and to its substitute technology, available in the market. The multi-criteria structure containing the set of principles, criteria and quantitative indicators chosen to assess the environmental performance of an innovation and its substitute technology are presented in Fig. 2. The set of indicators are related to environmental issues that concern agriculture, agro-industry or final disposal activities. Some of them are more relevant to one activity while others can be used by anyone of the aforementioned activities.

As each phase of the innovation and of its substitute technology can take place in different watersheds, the environmental vulnerability analysis is performed for each concerned one. The vulnerability analysis is based on a multi-criteria scheme that links environmental indicators to criteria and to a watershed Environmental Vulnerability Index (EVI) (Fig. 3).

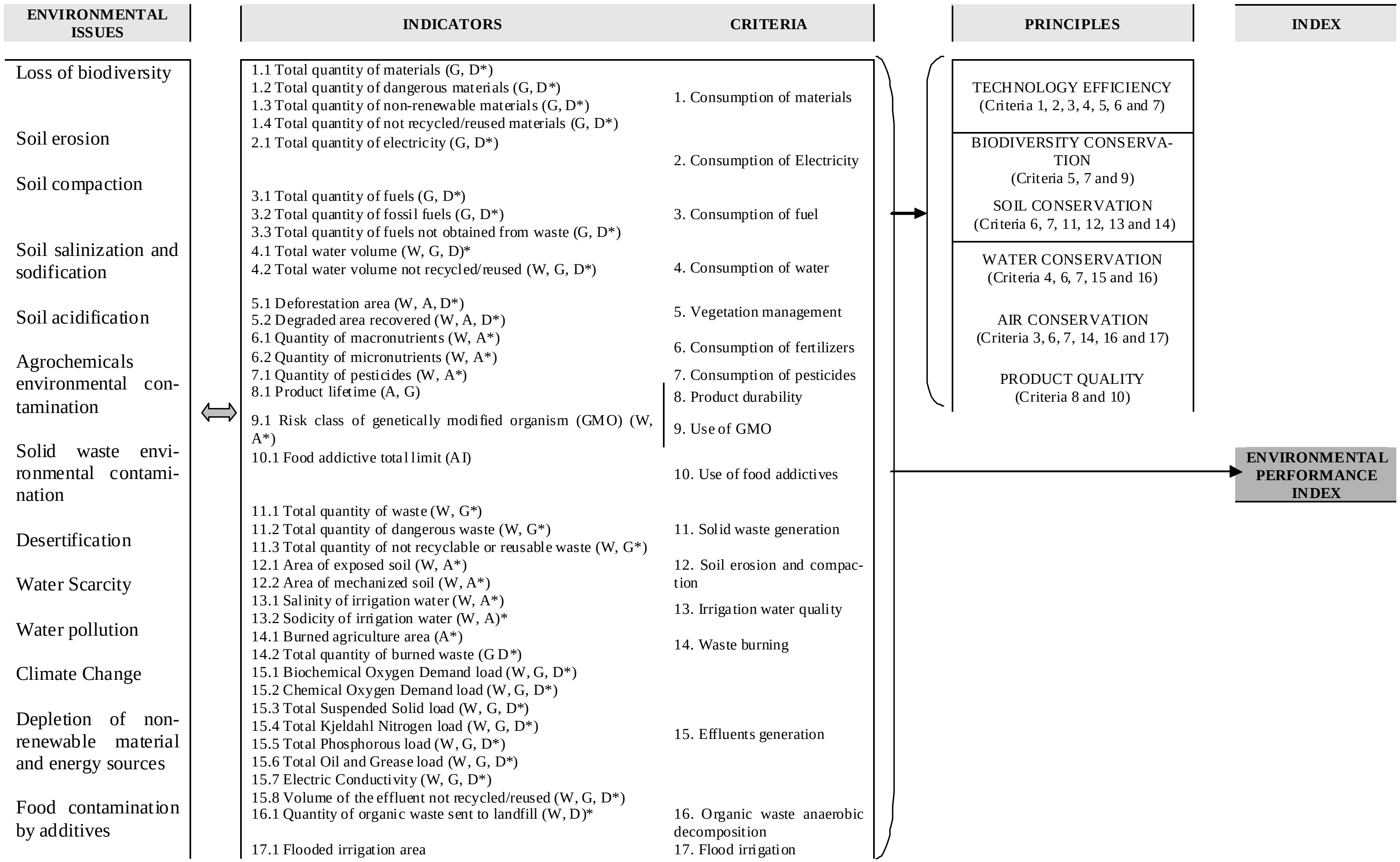
The EVI enters the performance evaluation of an innovation and of its substitute technology as a weight to those indicators that represent consumptions and emissions with potential to cause environmental impacts in the watershed area. These indicators are shown in Fig. 2. The higher the vulnerability of a watershed, the higher the potential effect of indicators related to environmental issues of relevant importance at the watershed level. This procedure highlights those consumptions and emissions of an innovation or its substitute technology that can lead to environmental impacts at the watershed level, when the watershed vulnerability is high.

The results of the analysis of each life cycle phase are aggregated to obtain a concluding environmental performance evaluation of an innovation and its substitute technology.



Where: I: Innovation; T: Substitute Technology

Fig. 1: Steps to implement the multi-criteria scheme of Ambitec-Life Cycle



* W - Environmental performance indicators that are weighed by a watershed environmental vulnerability index (EVI); A – indicators related to agriculture; AI – indicators related to agro-industry; G – indicators related to agro-industry and agriculture; D – indicators related to final disposal.

Fig. 2: Set of environmental performance indicators, criteria and principles available to the environmental performance evaluation of a technology

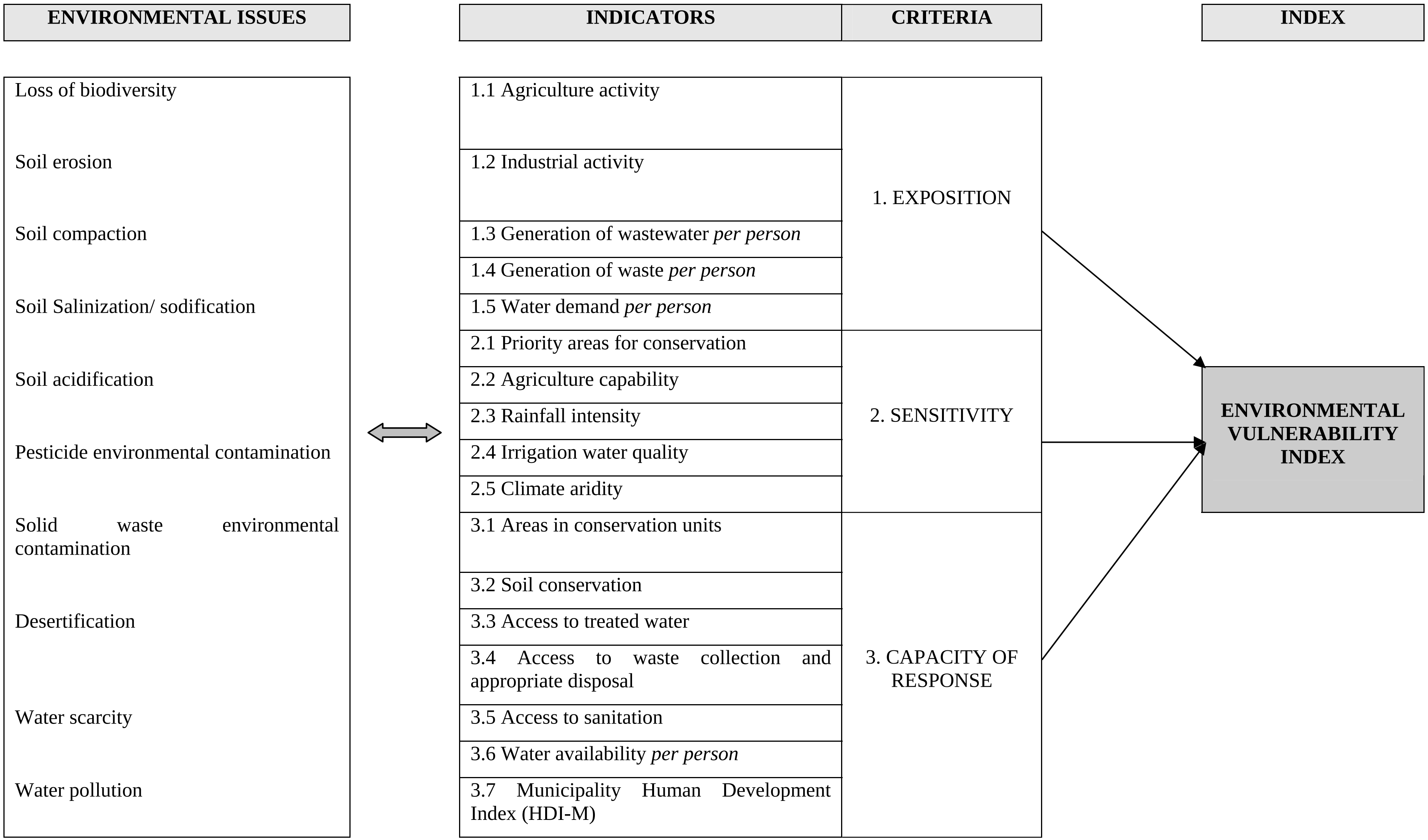


Fig. 3: Set of indicators and criteria to perform a watershed environmental vulnerability analysis

The main steps necessary to implement the Ambitec-Life Cycle method are:

i) Evaluation planning

The planning step of an innovation environmental performance evaluation begins with the definition of its function, functional unit, substitute technology and the reference flow. A function of an innovation is defined looking at its purpose when adopted. The functional unit is a quantification of an innovation (process or product) function. A substitute technology is chosen because it has a function similar to that of an innovation. The reference flow is the measure of intermediate and final products necessary to fulfil an established functional unit. An innovation and its substitute technology have a common function and functional unit and specific reference flows.

The next step is the choice of the production and disposal units for data collection on the environmental performance indicators. Finally, the watersheds where each unit is located are identified.

ii) Watershed vulnerability analysis

To carry out the vulnerability analysis, it is first necessary to gather data related to the set of vulnerability indicators.

Because each indicator has a different measuring unit, they must be normalized to a common dimensionless scale in order to allow their aggregation in criteria and in a watershed EVI. This index enters as a weighing factor in the environmental performance evaluation of an innovation and its substitute technology, in a given phase of their life cycle.

Vulnerability indicators can be quantitative (e.g. water demand and availability) or qualitative (e.g. agriculture capability and climate aridity). The “score range” rule, proposed by Malczewski (1999) is used to normalize the quantitative indicators of environmental vulnerability. This rule converts an indicator value to a standardized score in a scale ranging from 1 to 2, where 1 represents the lowest vulnerability and 2, the highest. The maximum and minimum values are obtained from literature and from available national databases.

Quantitative indicators in the proposed method belong to one of two groups: “the higher their value, the higher the environmental vulnerability” and “the higher their value, the lower the vulnerability”. Formulas 1a and 1b are used to normalize indicators that belong to the first and second group, respectively.

$$Value_i = \left(\frac{indicator_i - Value_{\min}}{Value_{\max} - Value_{\min}} \right) + 1$$

(Formula 1a)

$$Value_i = \left(\frac{Value_{\max} - indicator_i}{Value_{\max} - Value_{\min}} \right) + 1$$

(Formula 1b)

In Formulas 1a and 1b, “$Indicator_i$” represents the measured value of vulnerability indicator *i*; “$Value_{max}$” is the maximum value that indicator *i* can assume; “$Value_{min}$” is the minimum value that indicator *i* can assume and “$Value_i$” is the normalized value of indicator *i*.

For the qualitative indicators, a score is attributed to each possible response, ranging from 1 to 2, according to the understanding of the situation representing lower or higher vulnerability.

When an indicator presents different vulnerabilities in different areas of a watershed, the final indicator vulnerability score is calculated using the simple arithmetic average, with the percentage of each area being multiplied by the vulnerability score of the area (Formula 2).

$$Vu\ln erability\_Indicator_i = \sum_{i=1}^{n} Value_i * weight_i$$ (Formula 2)

In Formula 2, "n" is the number of areas with different vulnerability values assumed by a particular indicator *i* in a watershed; "$Value_i$" is the normalized vulnerability value of indicator *i*; "$weight_i$" is the percentage of area presenting a particular vulnerability value for indicator *i* and "$Vulnerability\_Indicator_i$" is the final vulnerability value of indicator *i* in the watershed.

The simple arithmetic average is used to aggregate normalized vulnerability indicators in criteria, and the criteria in watershed vulnerability index. It is assumed that all indicators have the same importance in a particular criterion and that all criteria have the same importance in the formulation of the watershed vulnerability index.

iii) Phase environmental performance evaluation

The environmental performance evaluation of an innovation and of its substitute technology is performed in each life cycle phase. Initially, the values of the performance indicators gathered in the studied unit, usually related to a certain production mass, are adjusted to the production mass defined in the reference flow. A linear correlation is assumed between the production mass and the values obtained by the indicators in the field measurement.

In sequence, the indicators with potential to disturb the environment in a watershed scale are then multiplied by the EVI.

After adjusting and considering environmental vulnerability, the values of the environmental performance indicators are normalized to a standard non-dimensional scale. To normalize these indicators, the "maximum or minimum score" linear scale transformation, proposed by Malczewski (1999), is used. The "maximum score" transformation rule (Formula 3a) is used when "the higher the indicator value, the higher the environmental performance", while the "minimum score" rule is used when "the higher the indicator value, the lower the performance" (Formula 3b). These rules allow the conversion of different indicators' measurement units to a standardized score that ranges from 0 to 100, where 0 represents the worst performance and 100, the best.

$$Indicator\_normalized_i = \left(\frac{Indicator_i}{Value_{\max_i}} \right) * 100 \qquad \text{(Formula 3a)}$$

$$Indicator\_normalized_i = \left(\frac{Value_{\min_i}}{Indicator_i} \right) * 100 \qquad \text{(Formula 3b)}$$

In Formulas 3a and 3b, "$Indicator_i$" is the measured value of indicator *i* that was already adjusted and weighted by EVI and is related to an innovation or to its substitute technology; "$Value_{maxi}$" is the maximum value of indicator *i* and $Value_{mini}$" is the minimum value of indicator *i*, obtained by the comparison between the value assumed by the innovation and by its substitute technology; "$Indicator\_normalized_i$" is the normalized value of indicator *i*, when evaluating an innovation or its substitute technology.

The simple arithmetic average is used to aggregate normalized performance indicators in criteria, criteria in principles and in the phase environmental performance index. It is assumed that all indicators have the same importance in a particular criterion and that all criteria have the same importance in the formulation of principles and the final environmental performance index.

iv) Final environmental performance evaluation

Next, the values of each indicator, already adjusted and weighted by the vulnerability index, are aggregated into a total value that represents all life cycle phases. To aggregate the values assumed by an environmental performance indicator in each life cycle phase, one of two approaches are used: the sum of the values obtained by an indicator, when its measurement unit is related to mass, energy, volume and area; the simple arithmetic average of the values obtained by an indicator, for other measurement units (e.g. dS/m).

Finally , the same steps already described to a particular life cycle phase are followed, involving data normalization and aggregation, leading to the determination of the innovation and its substitute technology final environmental performance index.

Discussion and Conclusions

The presented Ambitec-Life Cycle method is a new approach to the environmental performance evaluation process of agro-industrial innovation. The method integrates life cycle thinking, vulnerability analysis, and the multi-criteria structure used by the Ambitec-Agro System, the current method being used for technology innovation impact assessments at Embrapa, Brazil.

From LCA theory, Ambitec-Life Cycle brought the expanded view that every product has a life cycle that must be considered when performing its environmental performance evaluation. The focus on just one phase of a product life cycle can mislead the performance evaluation of an innovation, because performance can be better in that single phase but worse in others. Hence, the environmental assessment of an innovation and its products, considering its entire life cycle, can reveal opportunities for technological improvements in all phases.

The proposed method also uses the LCA concepts of function, functional unit and reference flow that give a common base for comparison between an innovation and its substitute technology. This comparison is necessary because the intention is to promote the development and adoption of new processes and products that have a better environmental performance than existing ones. Without using these concepts, there is a risk of comparing technologies with little function resemblance and of gathering consumption and emissions data related to different quantities of the final products, making it difficult to interpret the results.

The vulnerability theory brought the perception that the magnitude of an impact depends on the ecological and socioeconomic characteristics of the area or ecosystem that provides the resources and receives the emissions related to a product life cycle phase. Analyzing the literature about the vulnerability concept, three main criteria were identified as important, at the watershed scale: exposure, sensitivity and capacity of response. The vulnerability analysis integrated in the Ambitec-Life Cycle method makes it feasible to simulate different scenarios for the innovation when adopted, according to the places where its life cycle may occur. This analysis can guide the innovation transfer process by revealing watersheds that are more or less vulnerable to a particular phase of an innovation life cycle.

From the Ambitec-Agro System, the proposed method brought the multi-criteria approach with the principles, criteria and indicators hierarchy. This favored the selection of criteria and indicators relevant to agro-industrial activities, their aggregation in sustainability principles and aggregation in a final environmental performance index.

In the environmental impact assessment study area, there is a large number of tools available that evaluate the environmental impact of development projects or policies, some that evaluate agro-industrial activities and a few that evaluate agro-industrial technological innovations. In this context, the Ambitec-Life Cycle method enriches the debate and the action in this area.

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