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Environmental performance evaluation of agro-industrial innovations – Part 2: methodological approach for performing vulnerability analysis of watersheds

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ABSTRACT

Environmental vulnerability analysis has been sparsely used in environmental performance evaluation (EPE) of technological innovations. The present paper proposes a methodological approach to carry out vulnerability analysis of watersheds and to integrate this analysis into methods of environmental performance evaluation of agro-industrial innovations. This approach is applied to the Ambitec-Life Cycle method, described in Part 1 (this issue) of this study. The case study of green coconut substrate compared to ripe coconut substrate, also described in Part 1 (this issue), is now presented considering the vulnerability analysis of the watersheds where the life cycle stages of these products occur. The integration of vulnerability analysis in Ambitec-Life Cycle contributes to a better understanding of the environmental aspects of agro-industrial technological innovations with potential to cause significant impacts in watersheds where these innovations are implemented.

1. Introduction

The environmental performance evaluation (EPE) of agro-industrial innovations is an important step in the technological innovation process. Numerous methods are available to conduct the EPE of technological innovations. Among these, some specifically address agricultural and agro-industrial innovations, such as the Ambitec-Agro (Rodrigues et al., 2003) and the Inova-tec (Jesus-Hitzschky, 2007) approaches, routinely applied in product or process evaluation at the Brazilian Agency for Agricultural Research – Embrapa. A more general approach to EPE is offered by life cycle assessment (LCA) methods such as the Ecoindicator 99 (Goedkoop and Spriensma, 2000), IMPACT 2002+ (Jolliet et al., 2003), EPS (Steen, 1999), TRACI (Bare, 2003) and EDIP 2003 (Potting and Hauschild, 2005).

Each of these methods presents specially appropriated scopes and sets of selected indicators, but none of them is directly designed to consider the vulnerability of local environments where technological innovations are implemented. The use of vulnerability analysis is still in its beginning in the environmental performance arena. According to Kværner et al. (Kværner et al., 2006), vulnerability studies are hardly carried out during project or technological evaluations, despite their potential to enlighten the very definition of impacts to be considered and the decisions on appropriate projects or technological alternatives in impact reports.

For example, an agro-industrial product or process that requires large amounts of water should not be developed or adopted in a semi-arid region. In such an environment, water scarcity, soil salinization, and desertification are restraining vulnerability aspects that impose important qualitative and quantitative considerations, e.g., how restraining is water availability? At which level do these resource limitations impede resource extraction for production and discharge of processing residues?

In fact, vulnerability studies have been developed in the last decade to support planning decisions in the most varied scopes and scales such as the vulnerability of regions to climate change (Metzger et al., 2006), mountain areas to environmental degradation (Li et al., 2006), aquifers to pesticide and nitrate contamination (Barreto, 2006), geosystems to morphological processes (Lima et al.,

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2000), regions to global change (Schoter et al., 2004; Metzger et al., 2006), suburban areas to industrial pollution (Tixier et al., 2005), watersheds to environmental degradation (Tran et al., 2002; Zielinski, 2002), reservoirs to eutrophication (Bennion et al., 2005; Figueirêdo et al., 2007), and ecosystems to environmental degradation (Villa and McLeod, 2002).

As approached in these studies, vulnerability analysis has been related to specific environmental concerns (climate change, erosion, water pollution, etc.) and applied at different scales (aquifers, watersheds, geosystems, ecosystems, etc.), denoting a variety of concepts, applications, and scopes of currently available literature.

The objective of the methodological research detailed in the present study is to propose an objective, quantitative approach to allow the analysis of watershed vulnerability and to integrate this analysis into EPE methods devoted to agro-industrial technological innovations. In that sense, this approach is applied to the newly developed Ambitec-Life Cycle, a multi-criteria method that considers life cycle thinking in the environmental performance evaluation of agro-industrial innovations (Part 1 (this issue)). The case study of green coconut substrate (GCS), compared to ripe coconut substrate (RCS) (Part 1 (this issue)), is now presented considering the vulnerability analysis of four Brazilian watersheds where the life cycle stages of these products occur. An analysis is performed to point out which environmental performance indicators have more potential to cause impacts on these particular watersheds, considering their environmental vulnerability.

2. Methodological approach to evaluate the environmental vulnerability of watersheds

2.1. Vulnerability concept and scale

In order to insert vulnerability analysis as a quantitative procedure in the EPE of agro-industrial innovations, the vulnerability conceptualization advocated by Adger (Adger, 2006) and Gallopin (Gallopin, 2006) has been adapted, so that environmental vulnerability is understood as the susceptibility of a watershed to degradation, evaluated by considering the local environment's:

- exposure to pressures, related to materials and energy consumption and pollutant emissions. The consumptions and emissions observed are those commonly associated with agro-industrial activities, but that can also be inherent to other activities that have the potential to cause environmental impacts in the watershed (e.g.: water demand, wastewater and solid waste generation);
- sensitivity to exerted pressures, evaluated by observing the main physical and biotic environmental characteristics (e.g.: soil types, climate, biodiversity) that occur in the watershed and interact with the considered pressures, making the system more or less vulnerable to such pressures;
- capacity of response, evaluated by the adoption of conservation measures by a local society that may enhance the watershed capability to better respond to the exerted pressures. It is also evaluated by the awareness and capability of the local society to understand and act upon the exposure and sensitivity of the local environment (e.g.: sewage facilities, water storage, and delimitation of conservation areas).

The scale in a vulnerability study can be delimited in a range of spatial or socio-economic levels (ecosystem, geosystem, watershed, neighborhood, territory, etc.) according to the objectives of the study. However, the watershed is specially suited to vulnerability studies because human activities and associated technologies can directly alter a watershed's water quantity and quality, or change soil and vegetation characteristics that affect water resources.

2.2. Multi-criteria structure

A literature review on sets of indicators related to agro-industrial environmental issues (Figueirêdo, 2008; Monteiro and Rodrigues, 2006) revealed that those most frequently relevant in a watershed context are: biodiversity loss, soil erosion, compaction, salinization, sodification, acidification, desertification, agrochemicals contamination, solid wastes, water scarcity, and water pollution. Thus, vulnerability indicators that allowed objective expression of a watershed exposure, sensitivity and capacity of response to these issues were chosen for the present study. An important additional consideration for the selection and organization of indicators was the availability of reliable data for public consultation in official databases. The indicators were organized under the criteria of exposure, sensitivity, and capacity of response.

A hierarchical multi-criteria structure based on the proposed vulnerability concept is presented in Fig. 1. The description of each indicator is presented in Appendix A.

Because indicator variables are usually represented by different measurement units, normalization to a common dimensionless scale is a typical step in order to allow aggregation in criteria and in a final integrated index. The vulnerability scale used ranges from 1 (low vulnerability) to 2 (high vulnerability). The rules used to perform the appropriate normalization and aggregation steps necessary for this index development are described in Figueirêdo et al (Figueirêdo et al., 2009).

2.3. Strategy for considering vulnerability analysis in the EPE of agro-industrial innovations

According to Malczewski (Malczewski, 1999), the EPE can be assessed using multi-criteria analysis where a set of environmental indicators are related to criteria or objectives and these to a final EPE index, that is used to support decisions about technological innovation adoption. Ambitec-Agro (Monteiro and Rodrigues, 2006), Inova-tec (Jesus-Hitzschky, 2007), and Ambitec-Life Cycle (Figueirêdo, 2008) are examples of EPE methods that use multi-criteria schemes to study the possible impacts of agro-industrial innovations. Although each EPE method based on multi-criteria analysis has different hierarchical structures connecting indicators, criteria, and a final index, and uses particular rules for normalization and aggregation, they all are based on measurable indicators that can be weighed by a vulnerability index. This vulnerability index can in turn function as a correction factor to translate a watershed susceptibility to studied environmental pressures.

Hence, the dimensionless value of the Watershed Environmental Vulnerability Index proposed in the present study can work as a multiplying factor to those indicators used in EPE of technological innovations, which represent consumptions and emissions with potential to cause environmental impacts in the watershed area (Fig. 2). This weighing procedure uses one of two rules, according to the following rationale: when 'the higher the vulnerability, the higher the environmental performance of an indicator', Equation (1a) is used; and when 'the higher the vulnerability, the lower the environmental performance of an indicator', Equation (1b) is used.

With this strategy, environmental performance indicators related to positive impacts (e.g., degraded area recovered) will increase the innovation performance in watersheds of high vulnerability. Conversely, environmental performance indicators related to negative impacts (e.g., water consumption, effluent generation) will decrease the innovation performance in watersheds of high vulnerability.

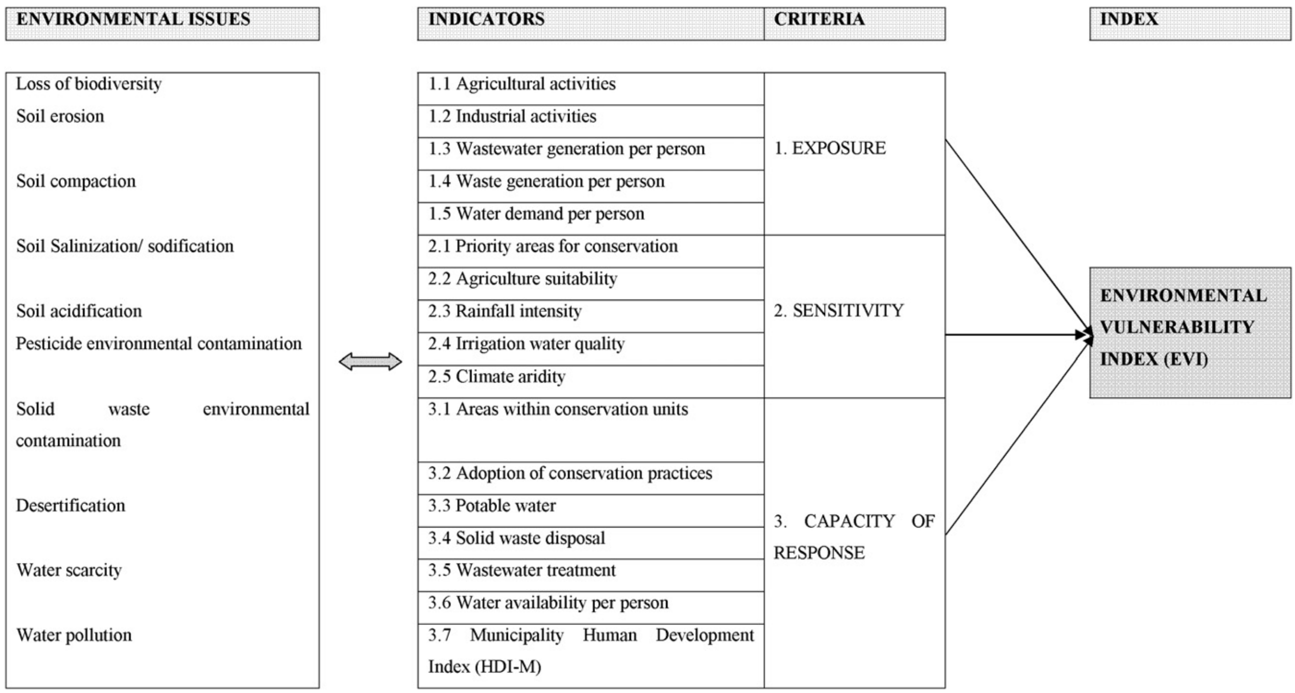

Fig. 1. Set of watershed environmental vulnerability indicators, organized in a multi-criteria structure.

$$\text{Weighed\_indicator}_i = \text{EPE\_indicator}_i * \text{EVI} \tag{1a}$$

$$\text{Weighed\_indicator}_i = \text{EPE\_indicator}_i * \frac{1}{\text{EVI}} \tag{1b}$$

In Equations (1a) and (1b), 'EPE_indicator$_i$' is the normalized value of an indicator 'i' in a particular EPE method that can cause relevant impact at the watershed level; 'EVI' is the dimensionless normalized value representing the environmental vulnerability of the watershed where the EPE of an innovation is being carried out; and 'Weighed_indicator' is the new modified value of an EPE indicator 'i' that was weighed by the watershed vulnerability index. The use of equation 1a can result in a score higher than the range used by an environmental performance multi-criteria method and, in this case, the maximum original score adopted by the method shall prevail.

3. Application of the proposed strategy to Ambitec-Life Cycle

The strategy proposed to insert vulnerability analysis in the EPE of innovations has been applied to Ambitec-Life Cycle, the method presented in Part 1 (this issue) of this study. This method evaluates the environmental performance of an agro-industrial technological innovation as compared with a current product or process, using a set of performance indicators organized in principles, criteria, and in a total environmental performance index. Ambitec-Life Cycle considers four life cycle stages of an innovation: (i) production/extraction of raw materials and resources used by the innovation; (ii) innovation production process; (iii) innovation utilization; and (iv) final disposal.

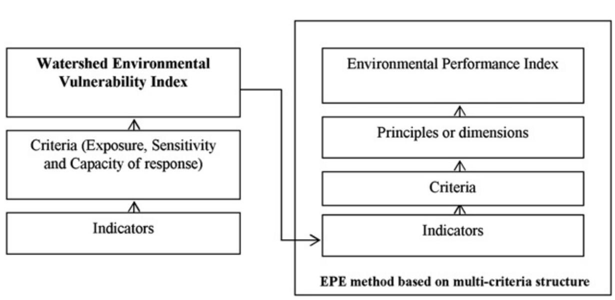

Fig. 2. Strategy for integrating the vulnerability analysis in the EPE of agro-industrial innovations.

The integration of vulnerability analysis within Ambitec-Life Cycle expands its framework, as presented in Fig. 3. At the left side of this figure, vulnerability analysis was introduced for each stage of the innovation as well as for its current product or process. The results of vulnerability analysis are then used in the environmental performance evaluation of the innovation and of its current product or process, performed in each of their life cycle stages and in their total analysis. At the right side of Fig. 3, a new step was introduced in Ambitec-Life Cycle original framework (described in Part 1 (this issue)) to carry out the vulnerability analysis and to integrate the environmental vulnerability index (EVI) in the procedures of environmental performance evaluation.

3.1. Case study of EPE of an agro-industrial innovation using the Ambitec-Life Cycle method expanded with vulnerability analysis

The proposed expanded framework of Ambitec-Life Cycle was applied to identify the influence of the watershed vulnerability in the performance evaluation of the agro-industrial innovation 'Green coconut substrate' (GCS), as compared to the current product 'Ripe coconut substrate' (RCS). Both substrates act as a physical support to seedlings and to plant production in soilless cultivation. The life cycle stages involved in the study of these products were: (i) coconut husks disposal (stage 1), (ii) substrate production (stage 2), (iii) substrate use in rose seedling production (stage 3a) and in rose production (stage 3b), and (iv) substrate final disposal in a composting area (stage 4). Part 1 (this issue) of this study presents details of the environmental performance evaluation of GCS and RCS.

In this case study the values of environmental performance indicators to each life cycle stage of these products were obtained in production units located at four different watersheds: Metropolitana, Parnaíba, Litoral, and Baixo Mundaú (Table 1). All these watersheds are located in the Brazilian Northeast, a region

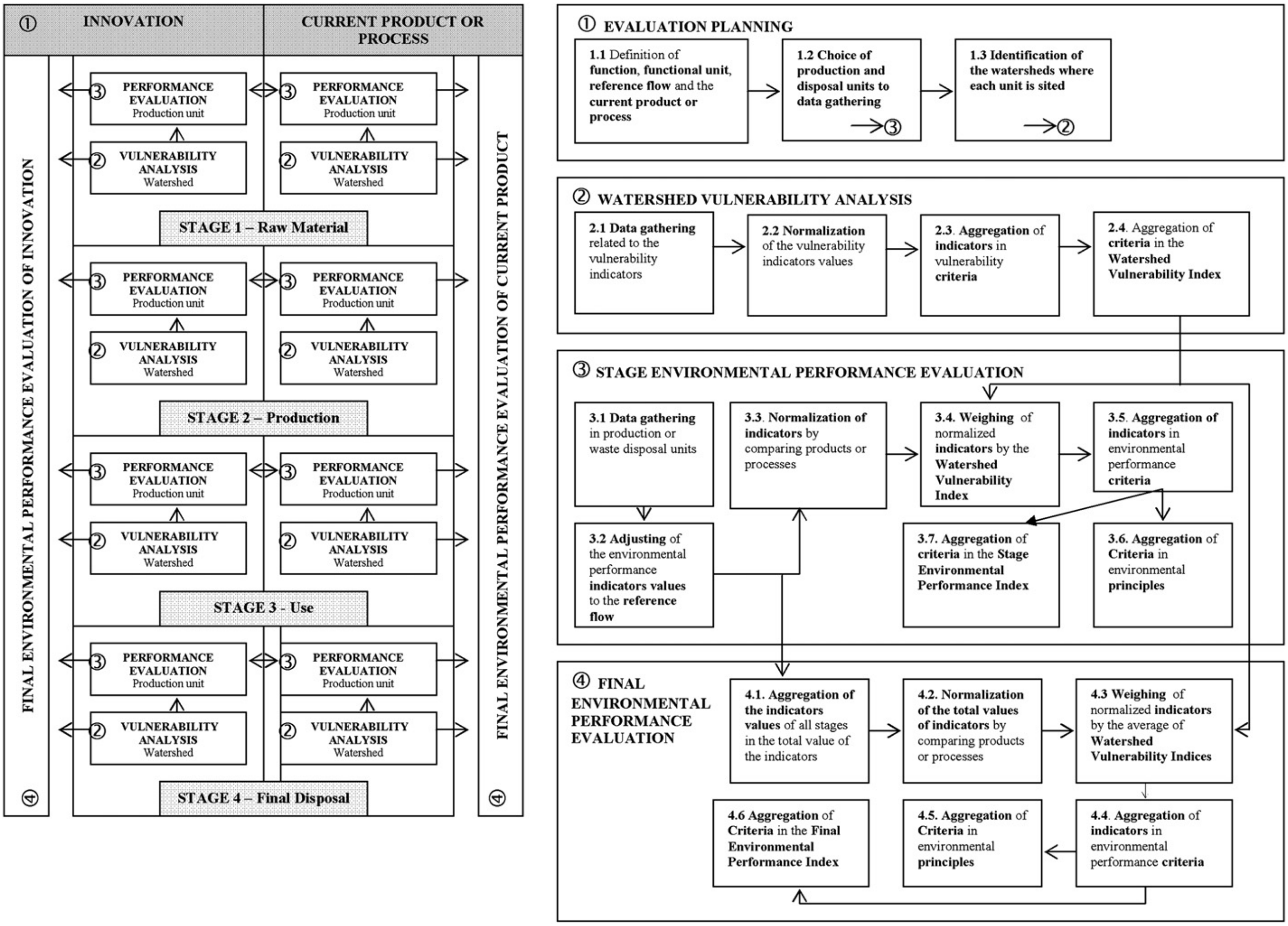

Fig. 3. Framework of Ambitec-Life Cycle, considering vulnerability analysis.

characterized by semi-arid climate with rainfall concentrated in few months of the year and a great part of its population presenting low income and literacy rates.

3.1.1. Vulnerability analysis of watersheds

The results of this analysis are shown in Table 2. Vulnerability analysis was performed in these watersheds using available databases as well as minimum and maximum values to quantitative indicators that are appropriate to the Brazilian environmental condition, presented in Appendix B.

The EVI obtained for these watersheds ranged from 1.52 in Baixo Mundaú to 1.57 in Metropolitana watershed. Although the variation range was narrow among the watersheds, important differences in the vulnerability criteria were perceived. For instance, three of the studied watersheds presented low vulnerability to exposure (Metropolitana-1.35, Litoral-1.29, and Parnaíba-1.24), with just Baixo Mundaú achieving a medium exposure (1.48), mainly explained by the important agricultural sector observed in this watershed. Sensitivity varied from low (Baixo Mundaú-1.34) to medium (Litoral-1.59) to high (Metropolitana-1.61 and Parnaíba-1.68). Higher sensitivity is related to higher rainfall intensity and climate aridity (especially in Parnaíba). All watersheds presented low capacity of response and consequently high vulnerability in this criterion (Metropolitana-1.73, Litoral-1.78, Parnaíba-1.73 and Baixo Mundaú-1.74), mostly related with modest investments in conservation units and low water availability.

3.1.2. Integration of vulnerability analysis in the EPE of GCS and RCS

The EVIs of these watersheds were integrated into the performance evaluation of GCS and RCS, according to the framework presented for Ambitec-Life Cycle in Fig. 3. It is worth to recall that the performance scale of Ambitec-Life Cycle ranges from 0 (worst performance) to 100 (best performance).

The EPE results of these products obtained by using the Ambitec-Life Cycle without vulnerability analysis (Part 1 (this issue) of this study) are compared with the EPE results using the expanded version of this method in Fig. 4. In the first situation, since vulnerability was not considered, it was as if all watersheds

Table 1
Watersheds related to each life cycle stage of GCS and RCS.

TECHNOLOGY	STAGE 1-Coconut substrate disposal	STAGE 2-Substrate production	STAGE 3a- Substrate use in rose seedling production	STAGE 3b - Substrate use in rose production	STAGE 4 - Substrate final disposal
GCS	Litoral	Metropolitana	Parnaíba	Parnaíba	Parnaíba
RCS	Metropolitana	Baixo Mundaú	Parnaíba	Parnaíba	Parnaíba

Table 2
Results of the vulnerability analysis of four Brazilian watersheds.

Criteria	Indicators	Weight of Indicators	Weight of criteria	Environmental Vulnerability—Metropolitana Watershed (State of Ceará)			Environmental Vulnerability—Litoral Watershed (State of Ceará)			Environmental Vulnerability—Baixo Mundaú Watershed (State of Alagoas)			Environmental Vulnerability—Parnaíba Watershed (State of Ceará)		
				Indicators	Criteria	EVI[a]	Indicators	Criteria	EVI[a]	Indicators	Criteria	EVI[a]	Indicators	Criteria	EVI[a]
1. Exposure	1.1 Agriculture activity	0.2	0.33	1.33	1.35	**1.57**	1.32	1.29	**1.55**	1.65	1.48	**1.52**	1.06	1.24	**1.55**
	1.2 Industrial activity	0.2		1.09			1.01			1.00			1.00		
	1.3 Wastewater generation per person	0.2		1.48			1.13			1.42			1.19		
	1.4 Waste generation per person	0.2		1.78			1.97			1.71			1.90		
	1.5 Water demand per person	0.2		1.06			1.01			1.60			1.06		
	Total =	**1**													
2. Sensibility	2.1 Priority areas for conservation	0.2	0.33	1.47	1.61		1.40	1.59		1.41	1.34		1.52	1.68	
	2.2 Agriculture suitability	0.2		1.63			1.58			1.28			1.69		
	2.3 Rainfall intensity	0.2		1.80			1.80			1.78			1.87		
	2.4 Irrigation water quality	0.2		1.54			1.50			1.14			1.61		
	2.5 Climate aridity	0.2		1.63			1.65			1.12			1.72		
	Total =	**1**													
3. Capacity of Response	3.1 Areas in conservation units	0.14	0.33	1.99	1.73		2.00	1.78		1.99	1.74		1.99	1.73	
	3.2 Adoption of conservation practices	0.14		1.78			1.88			1.92			1.89		
	3.3 Potable water	0.14		1.57			1.58			1.45			1.41		
	3.4 Solid waste disposal	0.14		1.65			1.68			1.66			1.58		
	3.5 Wastewater treatment	0.14		1.80			1.93			1.79			1.86		
	3.6 Water availability per person	0.14		2.00			2.00			1.99			1.99		
	3.7 Municipality Human Development Index (HDI-M)	0.14		1.34			1.38			1.40			1.36		
	Total =	**1**	**1**												

[a] EVI = Environmental Vulnerability Index.

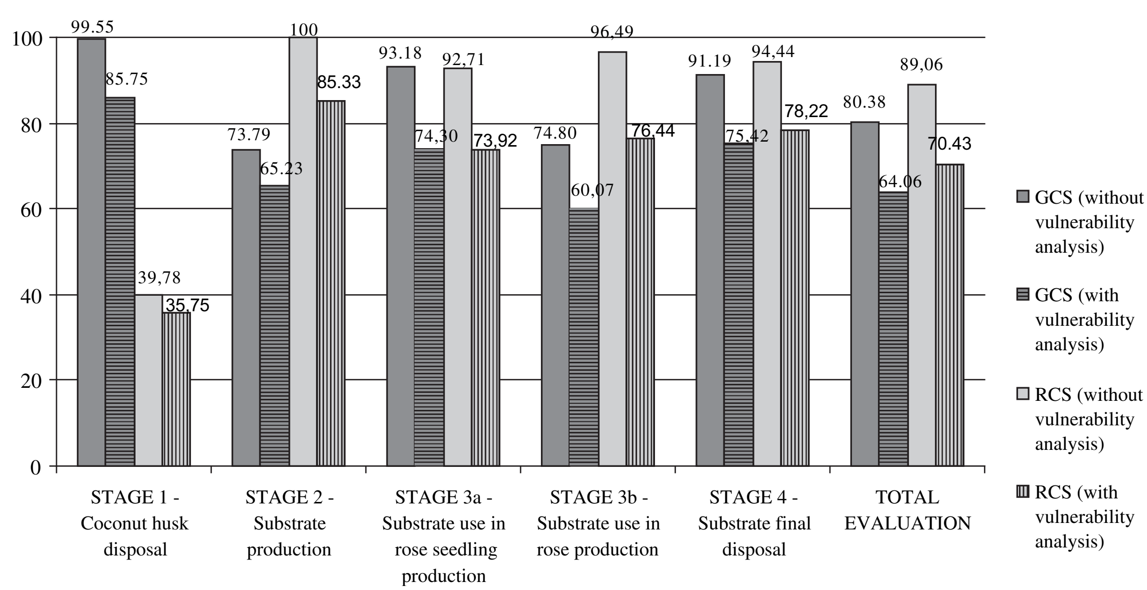

Fig. 4. Environmental performance along the life cycle stages of GCS and RCS without and with vulnerability analysis integration.

involved in the study presented the lowest vulnerability (equal to one). When vulnerability analysis was introduced, since the EVI scores of the involved watersheds were around 1.5, the environmental performance index of both products were reduced, in all stages of their life cycles and in the total EPE stage.

The total EPE of the studied products performed with vulnerability analysis showed that when all stages are considered, the performance of GCR was lower than the performance of RCS. This occurred because the average EVI for GCS, considering the vulnerability of the watersheds involved in each one of the GCS life cycle stages (Table 1), was higher (1.56) than the average EVI obtained for RCS (1.54). This result corroborated the result obtained by the evaluation without vulnerability analysis (Part 1), where RCS showed advantages over GCS.

Analyzing the performance of the studied products at each life cycle stage, the GCS continued to perform higher than RCS in stages 1 and 3a, and lower in stages 2, 3b and 4, when vulnerability was considered. To understand which environmental aspects of GCS have more potential to cause positive and negative impacts in the studied watersheds, each life cycle stage is analyzed next.

3.1.2.1. Effects of vulnerability analysis in stage 1 (coconut husk disposal). In stage 1, the vulnerability analysis showed that the EVI of the Metropolitana watershed, where the green coconut husks were disposed in a landfill, is higher than the EVI of Litoral, where ripe coconut husks were incorporated into agricultural soils. These vulnerability results reinforce the comparative advantage of using green instead of ripe husks as raw material for the production of substrate, since green husks are diverted from landfills.

The use of green coconut husks implies that there will be no disposal of this material in landfills and, consequently, no leachate generation and lower water levels, fossil fuels and energy consumption. The generation of leachate, by green coconut husk anaerobic degradation, has great potential to contribute to water pollution in the Metropolitana watershed that already presents medium vulnerability (1.48) to wastewater generation and high vulnerability (1.80) to wastewater treatment (Table 2). The consumption of water should also be avoided in the Metropolitana watershed that presents low water availability per person (2.0).

3.1.2.2. Effects of vulnerability analysis in stage 2 (substrate production). In stage 2, GCS performed lower than RCS when vulnerability was considered, since the EVI of Metropolitana, where GCS was produced, was higher (1.57) than the EVI of Baixo Mundaú (1.52), where RCS was produced. Considering that the production of GCS presented higher consumption of water and higher generation of solid wastes and effluent polluting load than RCS (Part 1), the potential impact of these aspects in a watershed, such as Metropolitana, was higher. In this watershed, water availability was already very low, wastewater treatment and waste facilities were insufficient and waste generation was higher (Table 2).

3.1.2.3. Effects of vulnerability analysis in stages 3 (substrate use) and 4 (substrate disposal). In stage 3a (substrate use in rose seedling production), both products were adopted by the same production unit located in the Parnaíba watershed. Although the performance of these products was reduced with vulnerability analysis, the advantage of GCS over RCS was maintained. Despite GCS' better performance, it is important to notice that the impact of water consumption (used in the washing of GCS before rose seeding production) was significant in Parnaíba which presented high vulnerability to climate aridity and water availability (Table 2).

Stages 3b (substrate use in rose production) and 4 also occurred in the same production unit, located in the Parnaíba watershed. The performance of both products decreased, but the GCS continued to perform lower than the RCS. Attention should be given to the high volume of water demanded by GCS and high effluent polluting load generated when irrigation water was drained and the GCS was washed to reduce its electrical conductivity in rose production. These environmental aspects have great potential to contribute to water scarcity and pollution in the Parnaíba watershed, which presented high vulnerability to water availability and wastewater treatment (Table 2).

In stage 4, the larger amount of GCS refused after two years of rose production required larger areas for composting fields. Care should be taken in the choice of the composting area to avoid using good quality agricultural or forested areas. Parnaíba watershed presented high sensitivity and vulnerability to agriculture suitability and medium sensitivity and vulnerability to priority areas for conservation.

3.1.2.4. Overall effects of vulnerability analysis in the EPE of GCS and RCS. The integration of vulnerability analysis in the environmental performance of GCS shows that the environmental performance indicators that received low scores, related to water consumption and waste and effluent generation, present great potential to significantly impact the studied watersheds (Metropolitana, Litoral, and Parnaíba). These watersheds are already vulnerable to the occurrence of water scarcity events and water pollution, as well as contamination by inadequate solid waste disposal. Further research to reduce water consumption, as well as to reduce emission and reuse effluents and wastes generated along GCS life cycle stages, shall be carried out by R&D teams in order to improve the innovation performance and to minimize its pressure upon natural resources in the involved watersheds.

Because these substrates can be produced and used in seedling and plant production all over Brazil, especially in the coastal areas, vulnerability analyses should be carried out in the other watersheds. This action would shed light on which watersheds GCS would probably cause smaller impacts, before research actions define new processes and product characteristics that could improve its environmental performance.

4. Discussion and conclusion

Any attempt to measure vulnerability implies judgments about which issues to include and which threshold values to adopt. This fact, however, does not reduce scientific debates and attempts to develop methods for conducting vulnerability analysis, that have been increasingly used in a range of disciplines, as a tool for decision making (Adger, 2006). In the environmental area, different interpretations of this term and measurement methods have been developed, especially to help prioritization of actions in regions affected by global change (Metzger et al., 2006; Schoter et al., 2004), by ecosystem change (Villa and McLeod, 2002), and by water eutrophication (Bennion et al., 2005; Figueirêdo et al., 2007).

The main benefits of adopting the proposed environmental vulnerability strategy is the knowledge gained about which environmental aspects (covered by performance indicators) could most probably cause significant impact in the natural resources at the watershed level. Without vulnerability analysis, an EPE method indicates critical environmental aspects of an organization management system, a project, an activity or an innovation, but hardly correlates these aspects with impacts in a regional scale. This correlation may better support decisions about which aspects to prioritize in management actions.

EPE methods based on qualitative analysis (e.g., methods based on descriptive checklists or Battelle Columbus matrices (Canter, 1996) do not benefit from the proposed strategy, since indicators are not measured. However, a vulnerability study can still help the team that conducts EPE studies based on such methods, because it allows a better understanding of the surrounding environment where innovation can be adopted. The accomplishment of a vulnerability analysis always attracts the attention of the EPE team in a research institute to those characteristics of a watershed that make it more vulnerable and, consequently, facilitate the shaping of innovations to perceived environmental constraints.

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Appendix A. Description of vulnerability indicators.

Indicators	Description	Calculation procedure
1.1 Agricultural activities	This indicator evaluates the pressure exerted by agriculture and animal husbandry in a watershed. Agriculture activities represent a pressure factor in a watershed due to deforestation and land clearing, which can lead to biodiversity loss, cause soil degradation (erosion, salinization, and sodification) through inappropriate plowing and irrigation techniques, and can contribute to climate change and environmental contamination by agrochemicals.	Agriculture_activity$_i$ = (agriculture_area$_i$/municipality_area$_i$)*100 Where 'agriculture_area$_i$' is the area (in hectares) devoted to crops, pastures, and silviculture in municipality 'i' of the studied watershed; 'municipality_area$_i$' is the area of municipality 'i' in hectares, and 'agriculture_activity$_i$', the percentage area of municipality 'i' devoted to agriculture. These data are commonly published at government agriculture agencies and the indicator ranges from 0% (minimum value) to 100% (maximum value).
1.2 Industrial activities	This indicator evaluates the pressure exerted by industry in a watershed. Industrial activities are important pressure factors, due to release of contaminants that can pollute soil, air, and water, as well as cause deforestation, biodiversity losses, and soil degradation (mainly extractive industry).	Industrial_activity$_i$ = employed_people$_i$/municipality_area$_i$ Where 'employed_people$_i$' means the number of people employed in extractive and transformation industries in municipality 'i' in the studied watershed; 'municipality_area$_i$' is the area of a municipality 'i' and 'Industrial_activity$_i$', the number of people employed in these industries by area unit in the watershed. These data are usually researched by government statistic offices.
1.3 Wastewater generation per person	This indicator computes the intensity of wastewater generation in a watershed. This indicator is nearly related to the water quality level in a watershed, since more wastewaters require larger water volumes to dilute pollutants, a critical problem especially in semi-arid regions. Generation of large amounts of wastewaters in a watershed is expected to cause water pollution, especially in regions where there is no appropriate treatment facilities.	Wastewater_generation$_i$ = collected_volume$_i$(m^3/year)/population_reached$_i$(hab) Where 'collected_volume$_i$' is the total sewage volume collected by year in municipality 'i' in the studied watershed; 'population_reached$_i$' is the number of people with access to wastewater treatment in municipality 'i', and 'Wastewater_generation$_i$' is the wastewater volume generated by person in municipality 'i'.
1.4 Solid waste generation per person	This indicator evaluates the intensity of solid waste generation in a watershed. Even when correctly disposed (landfills or incinerators), solid wastes can emit odors, global warming gases, and effluents rich in organic and inorganic pollutants. Solid waste generation leads to soil and water pollution in a watershed, especially in regions where appropriate solid waste treatment facilities are scarce.	Solid_waste_generation$_i$ = collected_mass$_i$(kg/day)/population_reached$_i$(hab) Where 'collected_mass$_i$' is the mass of solid wastes collected by day in municipality 'i' in the studied watershed; 'population_reached$_i$' is the number of people with access to solid wastes collection in municipality 'i'; 'Solid_waste_generation$_i$' is the mass of solid wastes generated per person in municipality 'i'.
1.5 Water demand per person	This indicator evaluates the intensity of water demand in a watershed. Water demand represents the volume of water required by population, agriculture, animal husbandry and industry in a watershed. Elevated water demands impact water reserves in a watershed, contributing to supply shortage events.	Water_demand = watershed_water_demand(m^3/year)/watershed_population (hab) Where 'watershed_water_demand' is the volume of water demanded by all users in a watershed (population, husbandry, agriculture and industry) in a year; 'watershed_population' is the population of all municipalities in the watershed, and 'Water_demand' is the yearly amount of water demanded per person in the watershed.
2.1 Priority areas for conservation	This indicator evaluates the existence and extension of priority areas for biodiversity conservation in a watershed. Main areas for conservation are those with relevant biodiversity (occurrence of endemism, of rare or endangered species, of migratory species, and of traditional cultural sites) and high sensitivity to degradation.	These areas are classified in five conservation priority classes (MMA, 2006), and were attributed vulnerability values (ranging from 1 to 2 in the adopted scale) as follows: (i) not prioritized (vulnerability = 1.2); (ii) insufficiently known (vulnerability = 1.4); (iii) high priority vulnerability = 1.6); (iv) very high priority (vulnerability = 1.8) and (v) extreme priority (vulnerability = 2).
2.2 Agriculture suitability	This indicator evaluates the feasibility of agriculture in an area based on studies of soils susceptibility to erosion, compaction, acidification and salinization; soil characteristics such as depth, drainage, texture, permeability, salts and organic material concentration; precipitation; topography, and vegetation type. As agriculture suitability studies classify soil types in groups, according to agriculture suitability, each group was attributed to a vulnerability value.	The defined agriculture suitability groups and their adopted vulnerability values are: group 1, soils suited for agriculture (vulnerability = 1); group 2, soils regularly suited for agriculture (vulnerability = 1.2); group 3, soils with restricted suitability for agriculture (vulnerability = 1.4); group 4, soils with good, regular or restricted suitability for planted pasture (vulnerability = 1.6); group 5, soils with good, regular, or restricted suitability for silviculture or natural pasture (vulnerability = 1.8) and group 6, soils not suited for agricultural uses (vulnerability = 2).
2.3 Rainfall intensity	This indicator evaluates the intensity of precipitation in a period of time along a watershed. Accordingly to Crepani et al (Crepani et al., 2004), high precipitation in a small period of time increases runoff, leading to soil erosion and compaction. Thus, high rainfall intensity in a region contributes to its higher sensitivity and vulnerability. Rainfall in semi-arid regions is usually concentrated in time.	$\text{Rain\_intensity}_i = \frac{\left(\sum_{j=1}^{n} \frac{\text{Annual\_pluviometry}_j}{\left(\frac{\text{Days\_with\_rainfall}_j}{30}\right)}\right)}{n}$ Where 'Annual_pluviometry$_j$' means the millimeters of rainfall in year 'j'; 'n' is the number of years of historical data; 'Days_with_rainfall$_j$' is the number of days that rained in year 'j' and 'Rainfall_intensity$_i$' is the rainfall intensity measured in site 'i', located in or near the studied watershed. The representative area of a particular meteorological monitoring point in a watershed can be measured by calculating Thiessen polygons in the watershed map, according to Miranda (Miranda, 2005).

(*continued*)

Indicators	Description	Calculation procedure
2.4 Irrigation water quality	This indicator represents the water quality available for irrigation in a watershed, considering its salinity and sodicity. The risk of soil salinization or sodification is given by potential of water to cause these effects, according to Ayres and Westcot (Ayers and Westcot, 1991). Thus, a higher water salinity or sodicity leads to a higher watershed vulnerability to soil salinization or sodification. Irrigation water quality is based on two parameters: water salinity, evaluated measured electric conductivity (EC); and water sodicity, evaluated by measuring water EC and the sodium adsorption ratio (SAR). A watershed whose water bodies present high EC is more sensitive and vulnerable to soil salinization. When water bodies present low EC for a given SAR, the watershed is more sensitive to soil sodification (Ayers and Westcot, 1991).	Water salinity ranges from 0.1 (minimum value) to 3 dS m^{-1} (maximum value), according to the range of values observed by Ayres and Westcot (Ayers and Westcot, 1991). The vulnerability to soil sodification in a particular watershed area, influenced by a water monitoring point, is calculated according to Ayres and Westcot (1991), combining EC and SAR values: - Vulnerability = 1 (low): when SAR 0 to 3 and EC > 0.7; SAR 3 to 6 and EC > 1.2; SAR 6 to 12 and EC > 1.9; SAR 12 to 20 and EC > 2.9; and, SAR 20 to 40 and EC > 5; - Vulnerability = 1.5 (medium): when SAR 0 to 3 and EC 0.7 to 0.2; SAR 3 to 6 and EC 1.2 to 0.3; SAR 6 to 12 and EC 1.9 to 0.5; SAR 12 to 20 and EC 2.9 to 1.3; and, SAR 20 to 40 and EC 5 to 2.9; - Vulnerability = 2 (very high): when SAR 0 to 3 and EC < 0.2; SAR 3 to 6 and EC < 0.3; SAR 6 to 12 and EC < 0.5; SAR 12 to 20 and EC < 1.3; and, SAR 20 to 40 and EC < 2.9. The influence area of a particular EC and SAR monitoring point in a watershed can be measured by calculating Thiessen polygons, according to Miranda (Miranda, 2005). The final normalized vulnerability value in each watershed area is obtained by the arithmetic average of salinity and sodicity vulnerability values obtained for that area.
2.5 Climate aridity	This indicator evaluates the average climate class of a watershed. Regions in arid and semi-arid climates are more sensitive and vulnerable to water scarcity, soil salinization and sodification, and desertification processes. The United Nations uses this indicator to identify areas susceptible to water scarcity and desertification (MMA, 2004).	Watershed vulnerability is evaluated by attributing different vulnerability values to each one of its areas dominated by climate risk classes: area with arid climate (vulnerability = 2); area with semi-arid climate (vulnerability = 1.8); area with sub-humid dry climate (vulnerability = 1.6); areas surrounding arid and semi-arid climate (vulnerability = 1.4); areas with other climates (vulnerability = 1).
3.1 Areas within conservation units	This indicator evaluates the commitment of municipalities in a watershed with conservation of natural habitats. Areas legally protected receive formal intervention preventing natural resource exploitation.	Three conservation area types are considered: integral protection areas, where very limited human intervention is allowed (vulnerability = 1.2); areas partially protected, where some human intervention is allowed (vulnerability = 1.6); areas not protected, where any human intervention is allowed (vulnerability = 2).
3.2 Adoption of conservation practices	This indicator evaluates the use of soil and vegetation conservation practices in a watershed. Adoption of conservation practices is measured considering the following actions in the watershed: deforestation prevention; degraded forests recovery; salinization, compaction and erosion processes' prevention or remediation; agrochemical use control, and use of agricultural practices to prevent organic soil matter losses.	When all these actions are carried out, it is assumed that the local community is aware of conservation practices and its capacity of response is high (vulnerability = 1). Conversely, if none of these actions is adopted, the community has low capacity of response (vulnerability = 2). If some of these actions are adopted, capacity of response is considered medium (vulnerability = 1.5). These data can be gathered from the municipalities' agriculture agencies, at the watershed management committee, or at government published researches.
3.3 Potable water	This indicator evaluates the access of the population living in a watershed to potable (properly treated) water, by measuring two parameters: access to water distribution system (the percentage of population with access to water distribution system) and access to treated water (the percentage of the total distributed water that was properly treated). These parameters are complementary, since a wide access to a water distribution system does not guarantee proper treatment, which involves at least the processes of flocculation, decantation, filtration, and disinfection. Access to potable water is important to human health, especially where water bodies receive improperly treated effluents.	$Access\_water\_distribution_i = (population\_access_i(hab)/population\_municipality_i(hab))*100$ Where 'population_access$_i$' is the number of people in municipality 'i' with access to water distribution system; 'population municipality$_i$' is the number of people in municipality 'i', and 'Access_water_distribution$_i$' is the percentage of the population with access to water distribution system in municipality 'i'. $Treated\_water_i = (volume\_water\_treated_i(m^3/day)/volume\_water\_distributed_i(m^3/day))*100$ Where 'volume_water_treated$_i$' is the volume of water that received appropriate treatment (at least flocculation, decantation, filtration, and disinfection) in municipality 'i' in the studied watershed; 'volume_water_distributed$_i$' is the volume of water distributed by the public system in municipality 'i'; 'Treated_water$_i$' is the percentage of the distributed water that was properly treated in municipality 'i'. These data are usually available in water distribution agencies or government offices. Both parameters (Access_water_distribution$_i$' and 'Treated_water$_i$') range from 0% (minimum value) to 100% (maximum value) in a municipality. The final vulnerability value of this indicator in a municipality is obtained by calculating the average mean of the normalized vulnerability values related to both analyzed parameters.
3.4 Solid waste disposal	This indicator evaluates the population access to solid wastes collection and to adequate disposal, by measuring two parameters: access to solid wastes collection and access to appropriate disposal. Solid wastes not collected or inadequately disposed cause soil and water contamination, as well as air pollution. An efficient solid waste management system indicates a good capacity of response of local society to minimize the potential impact of solid wastes generation.	$Access\_collection_i = (population\_reached_i/population\_municipality_i)*100$ Where 'population_reached$_i$' is the number of people served by a solid wastes collection system in a municipality 'i'; 'population municipality$_i$' is the number of people in municipality 'i', and 'Access_collection$_i$' is the percentage of the population with access to solid wastes collection system in municipality 'i'. $Solidwaste\_disposal_i = mass\_appropriately\_disposed_i(t/day)/mass\_collected_i(t/day)*100$ Where 'mass_appropriately_disposed$_i$' is the mass of solid wastes sent to recycling, composting, incineration or controlled landfill in municipality 'i'; 'mass_collected$_i$' is the mass of solid wastes collected by the public system in a municipality 'i', and 'Solidwaste_disposal$_i$' is the percentage of the total mass of solid wastes collected that was sent to an appropriate disposal in municipality 'i'. These data are usually available in the public agencies responsible for sanitation activities. Both parameters (Access_collection$_i$' and 'Solidwaste_disposal$_i$') range from 0% (minimum value) to 100% (maximum value) in a municipality. The final vulnerability value of this indicator in a municipality is obtained by calculating the average mean of the normalized vulnerability values related to the two analyzed parameters.

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Indicators	Description	Calculation procedure
3.5 Wastewater treatment	This indicator evaluates the percentage of the population that has access to wastewater treatment system in a watershed. The population access to a wastewater treatment system is an initial response to reduce sewage pressure on water bodies in a watershed.	$Access\_wastewater\_system_i = (poulation\_reached_i(hab)/poulation\_municipality_i(hab))*100$ Where, '$population\_reached_i$' is the number of people with access to wastewater treatment system in a municipality 'i'; '$population\_municipality_i$' is the number of people in municipality 'i', and '$Access\_wastewater\_system_i$' is the percentage of the population in municipality 'i' that has access to a wastewater treatment system. This indicator ranges from 0% (minimum value) to 100% (maximum value) in a municipality.
3.6 Surface water availability per person	This indicator evaluates surface water availability in a watershed. When a watershed has a management plan, investments are directed to increase surface water availability through construction of wells, dams and other equipment that allow water storage and supply in all seasons. Thus, higher surface water availability per person in a watershed is related to society capacity of response to prevent water scarcity events.	$Water\_availability = average\_flow(m^3/year)/watershed\_population(hab)$ Where 'average_flow' is the long-term annual average flow of the main river in a watershed (available 90% of the time in regulated rivers and in 95% of the time in non-regulated perennial rivers); 'watershed_population' is the population of a watershed; and 'Water_availability' is the volume of water yearly available per person in a watershed. These data are commonly available in watershed management plans or at national and state water management agencies.

Appendix B. Data sources to the proposed indicators and suggestions of minimum and maximum values to Brazil.

Indicators	Minimum value	Maximum value	Data sources
1.1 Agricultural activities	0%	100%	Agriculture Census (IBGE, 1996) and Demographic Census (IBGE, 2000)
1.2 Industrial activities	0 employees/km^2	125 employees/km^2	Central Companies Register (IBGE, 2009)
1.3 Wastewater generation per person	10 m^3.hab^{-1}.year^{-1}	100 m^3.hab^{-1}.year^{-1}	National Basic Sanitation Research (IBGE, 2000), National Basic Sanitation Information System - SNIS (SNIS, 2005).and Demographic Census (IBGE, 2000)
1.4 Waste generation per person	0.1 kg.hab^{-1}.day^{-1}	1.5 kg.hab^{-1}.day^{-1}	National Basic Sanitation Research (IBGE, 2000), National Basic Sanitation Information System - SNIS (SNIS, 2006) and Demographic Census (IBGE, 2000)
1.5 Water demand per person	30 m^3.hab^{-1}.year^{-1}	1.500 m^3.hab^{-1}.year^{-1}	Database of the Water National Agency - ANA (ANA, 2005), research performed by Rebouças (Rebouças, 2002) and Demographic Census (IBGE, 2000)
2.1 Priority areas for conservation*	1	2	Map of Priority Areas for Conservation (MMA, 2006)
2.2 Agriculture suitability*	1	2	Studies of agriculture suitability (Ministério da Agricultura, 1979)
2.3 Rainfall intensity	50 mm month^{-1}	525 mm month^{-1}	Northeast Hidroclimatic Database (SUDENE, 2008)
2.4 Irrigation water quality*	0.1 dS m^{-1} (water salinity)	3 dS m^{-1} (water salinity)	Database of the Water National Agency - ANA (ANA, 200))
2.5 Climate aridity*	1	2	Map of Areas susceptible to desertification in Semi-Arid (MMA, 2004)
3.1 Areas within conservation units*	1.2	2	Map of Protected Areas (IBAMA, 2009)
3.2 Adoption of conservation practices*	1	2	Brazilian Municipalities Profile (IBGE, 2002)
3.3 Potable water	0%	100%	National Basic Sanitation Research (BGE, 2000) and Demographic Census (IBGE, 2000)
3.4 Solid waste disposal	0%	100%	National Basic Sanitation Research (IBGE, 2000) and Demographic Census (IBGE, 2000)
3.5 Wastewater treatment	0%	100%	National Basic Sanitation Research (IBGE, 2000) and Demographic Census (IBGE, 2000)
3.6 Water availability per person	0 m^3.hab^{-1}year^{-1}	100.000 m^3. hab^{-1}year^{-1}	Database of the Water National Agency - ANA (ANA, 2006) and Demographic Census (IBGE, 2000)
3.7 Municipality Human Development Index (HDI-M)	1	2	Brazilian Atlas of Human Development (PNUD, 2003)

* Qualitative indicators with ranges described in Appendix A.

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