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The reliability of experts' opinions in constructing a composite environmental index: The case of ESI 2005

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A B S T R A C T

The complexity of the environment demands a well-constructed composite environmental index (CEI) to provide a useful tool to draw attention to environmental conditions and trends for policy purposes. Among the common difficulties in constructing a proper CEI are uncertainties due to the selection of the most representative underlying variables or indicators. A degree of uncertainty accompanies experts' judgments, and to deal with vague, subjective or inconsistent information, logic other than classic is required. This study analyzes a procedure that uses different experts' opinions in constructing a CEI, with the use of paraconsistent annotated logic. For this, a sensitivity analysis of the Environmental Sustainability Index (ESI 2005) was used as an example to assess the reliability of experts' opinions. The uncertainty due to the disagreement in experts' opinions clearly indicates that the forms we presently use to measure and monitor the actual environment are insufficient, that is, there is a lack of a "science of sustainability".

1. Introduction

Environmental sustainability is a growing concern that attracts efforts of researchers from several fields, comprising humanities, natural science, social science and engineering. One of these efforts is related to the construction of composite environmental indexes, CEIs, which aspire to offer condensed environmental information for decision making, performance monitoring, policy progress evaluation, and benchmarking comparisons. CEIs intend to provide insight into the state and dynamics of the environment and may include physical, biological and chemical indicators, but also comprise indicators of environmental pressures, states and societal responses. This kind of index intends to have the ability to isolate key aspects from a huge amount of information and help policy-makers to see patterns. Given the complexity of environment, a well-constructed CEI could provide a useful tool to highlight environmental conditions and trends for policy purposes. Several examples of well-known CEIs, used to rank countries, may be cited: the ecological footprint (Rees and Wackernagel, 1996), the surplus biocapacity measure (Wackernagel et al., 2005), the wellbeing index (Prescott-Allen, 2001), and the ecosystem service product (Sutton and Costanza, 2002).

The construction of a CEI is a dynamic process, which may be roughly simplified in three steps. In a first theoretical step, environmental experts are often involved for the purpose of selecting the most representative underlying variables (Yuan et al., 2003; Esty et al., 2005). In this moment, the environmental system is defined and the variables are selected and classified. The second step (operational step) involves data collection and handling. Once the environmental variables are normalized, the resulting variables could be aggregated into an overall index by some aggregating method. Then, in the final step, data are aggregated leading to a CEI that may help decision making, benchmarking for environmental performance and monitoring progress or changes in environmental systems to implement improvements or for policy making.

During the CEIs construction, however, some difficulties arise. A common difficulty one must deal is the uncertainty arising from incomplete data, limitations of measurement accuracy or available information, extrapolations, interpolations, and so forth. Despite of never completely eliminated, this kind of uncertainty can be reduced, by improving data or the accuracy of measuring devices or by taking more comprehensive surveys, that is, it can be reduced with the improvement of the quality and quantity of the available data. It is important to specify the uncertainty in any data set

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carefully, employing at least one of the various well-established and reliable methods available (Melchers, 1999; Mendenhall et al., 1990; Horwich, 1982; Walley, 1991). Another difficulty may be related to the determination of an appropriate aggregating method to combine multiple predictor environmental variables into a condensed index (den Butter and van den Eyden, 1998; Zhou et al., 2006). Despite the several CEIs proposed in the literature (van den Bergh and van Veen-Groot, 2001; Hope et al., 1992; Kang et al., 2002; Khanna, 2000), there is still a need of objective criteria for choosing a suitable aggregating method to enable international comparability (Giannetti et al., 2006; Almeida et al., 2007). In the theoretical step, to select and classify the variables that will compose a CEI a careful review of the science and the literature in the environmental field must be performed, along with consultation with many experts from across the environmental sciences, government, business, non-governmental groups, research centers, and the academic sector. Then, a different difficulty arises as experts assigned to select the most representative underlying variables or indicators may not agree on the nature of the variables to be selected or on the relative importance of one indicator among others. The difficulty here lies on the consistency of expert's opinions.

Expert weighting for environmental indicators quite often includes factors of subjective nature, inaccurate knowledge, sometimes even vague or conflicting information, which may lead to distorted opinions that eventually compromise the clarity and objectiveness of the analysis. For example, experts in business, environmental policies or academics will weight an indicator as "Reducing ecosystem stress" relying on their own interpretation of the environment. A degree of uncertainty accompanies the expert's judgment, as this expert estimates a determinate fact based on experience, knowledge of environmental systems, or anecdotal observation.

In order to logically handle a set of vague, subjective or inconsistent information, logic other than classic is required, once the latter cannot, at least directly, be applied for such purpose. Hence, paraconsistent annotated logic can, in principle, be an adequate tool for the task (Costa et al., 1999), see Section 2.2.

The purpose of this study is to analyze the procedure that employs different expert's opinions in constructing a CEI. With this respect, the Environmental Sustainability Index (ESI 2005) (Esty et al., 2005) brings a sensitivity analysis to assess the output variation due to the choice of weights, that is, equal weights or weights derived from experts' opinion. The sensitivity analysis of the ESI index is used as an example to assess the reliability of expert's opinions based on paraconsistent annotated logic. The paper is organized as follows. In Section 2 we introduce the ESI index, and some aspects of paraconsistent annotated logic. Section 3 describes the methodology and Section 4 presents the results and discussion about the influence of weighting by experts on the output results of composed environmental indexes.

2. Conceptual background

2.1. The ESI index

Among the CEIs found in the literature (Esty et al., 2005; van den Bergh and van Veen-Groot, 2001; Hope et al., 1992; Kang et al., 2002; Khanna, 2000), special attention has been directed to the Environmental Sustainability Index (ESI) which presents the results of a study that covers and ranks 146 countries and involves 76 underlying variables aggregated in 21 indicators (Fig. 1).

The ESI consists of five components: environmental systems, reducing environmental stresses, reducing human vulnerability, social and institutional capacity and global stewardship. Each of these components is made up of a number of indicators, which include indicators of physical, biological and chemical state, as well as indicators of environmental pressures, and the responses of society (Fig. 1). Indicators and variables on which components are constructed build on the well-established "Pressure–State–Response" environmental policy model. The issues incorporated and variables used were chosen through a careful review of the environmental literature, surveys of available data, rigorous analysis, and consultation with policymakers, scientists, and specialists (Esty et al., 2005).

Regarding the quality and quantity of data (uncertainty), the ESI recognizes that there are many sources of uncertainty including measurement error, systematic and human error as well as missing data. An uncertainty analysis aiming to quantify the overall variation in the countries' ranking resulting from the uncertainties in the model input was performed, and a Monte Carlo approach was used as it considers all uncertainty sources simultaneously. The simultaneity of the approach intended to capture all possible synergistic effects among uncertain input factors, including their interactions as well as individual effects (Esty et al., 2005).

With respect to the aggregation method, ESI 2005 employed the simple additive weighting method, which is considered as one of the most commonly used aggregating method for constructing a CEI (Kang et al., 2002). The robustness of the ESI was assessed with the evaluation of its sensitivity to the structure and aggregation methods utilized. To test this sensitivity, the effect of four main uncertainties was explored: variability in the imputation of missing data, aggregation at the indicator versus the component level, linear versus non-compensatory aggregation schemes, and equal versus expert weighting of indicators. ESI was settled on uniform weighting of the 21 indicators, as in the absence of exact expert information or mechanism to determine the relative importance of different environmental variables, the choice of equal weights is acceptable (Hope et al., 1992). The weights of the environmental variables used in the sensitivity test intended to reflect expert opinions or the public preferences for environmental issues.

2.2. Some aspects of paraconsistent logic

Paraconsistent logic is an inconsistency-tolerant logic that attempts to deal with contradictions in a discriminating way. Although not very known in engineering applications, paraconsistent logic is under concern of philosophers and mathematicians since its appearance in the beginning of the last century. Roughly speaking, while in classical logic contradictions entail everything, paraconsistent logic rejects the principle of non-contradiction.

Paraconsistent logic was first mentioned by J. Lukasiewicz and N. I. Vasiliev (Arruda, 1989; D'Ottaviano, 1990). In 1910, both have presented general ideas for the development of a paraconsistent logic discussing the possibility of violating the Principle of Contradiction. Later in 1948, Stanislaw Jaskowski constructed a system of propositional paraconsistent logic, where he distinguished between contradictory/inconsistent systems and trivial ones. In 1953 and 1954, Newton da Costa began the development of his ideas on paraconsistency motivated by mathematical problems, and developed the idea of paraconsistent logic as a field with relevant applications in applied science and technology, such as robotics (Nakamatsu et al., 2002), expert systems (Alcantara et al., 2005), and medicine (Sadegh-Zadeh, 2002).

The paraconsistent annotated logic (Costa et al., 1999) is a particular case of paraconsistent logic in which degrees of certainty (μ) and uncertainty (λ), of the proposition $p(\mu,\lambda)$, are assigned to each variable. This methodology allows the treatment

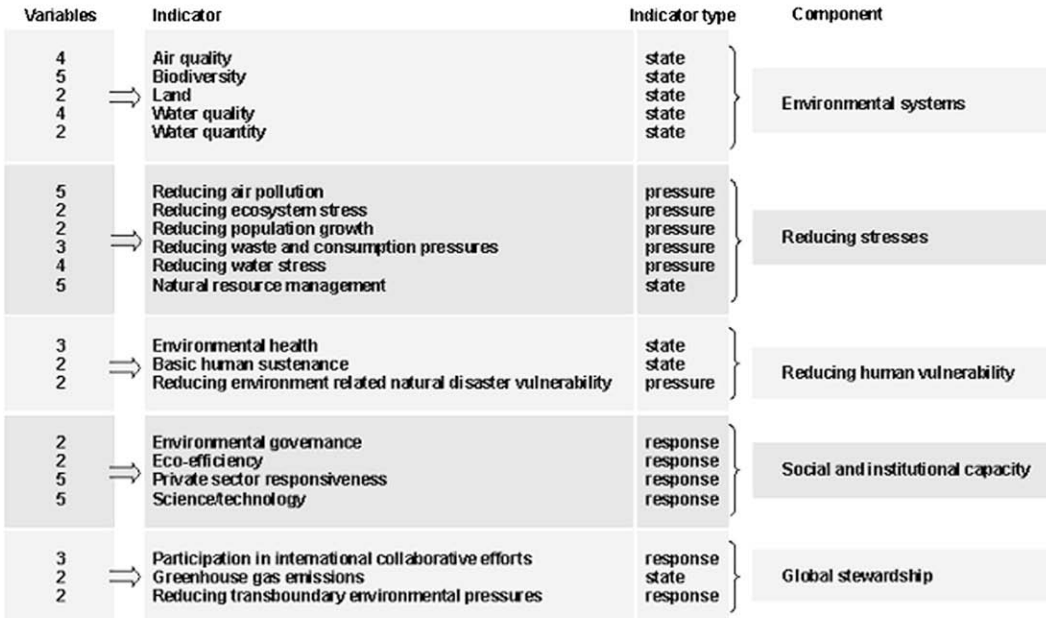

Fig. 1. Structure of the environmental sustainability index (ESI 2005): number of variables composing each indicator, indicators, indicators type, and components. Indicators of pressure-type denote the measure of human activities directly affecting the environment. State-type indicators measure observable changes of the environment, and response-type indicators correspond to the response of society to solve environmental problems. Adapted from Table 2 of World Economic Forum (2001).

of information containing factors of subjective nature, inaccurate knowledge, vague and conflicting information.

3. Methodology

3.1. Data source

The ESI 2005 (ESI) ranks 146 countries integrating 76 variables into 21 indicators of environmental sustainability. These 21 indicators were aggregated on uniform weighting employing the simple additive weighting method. A sensitivity analysis was performed to determine the influence of indicators weighting (Esty et al., 2005). Data regarding experts' opinions were obtained by survey at the December 2004 ESI Review Meeting. The expert rating of ESI indicators was obtained by averaging the opinion from 17 experts working on a broad spectrum of environmental sustainability and policy issues (Table 1). Experts received a "budget" of 100 points and asked to allocate them to the 21 indicators according to their personal judgment of the relative importance of the indicators (Esty et al., 2005).

3.2. Criteria for evaluating the degree of belief and disbelief

In paraconsistent annotated logic one assigns an annotation (μ,λ), such that μ and λ belong to the closed real interval [0;1]. Thus, given a proposition *p*, μ can be read as the degree of belief (or favorable evidence) of *p*, and λ the degree of disbelief (or contrary evidence) of *p*. In this way, annotations will define extreme states as follows: ($\mu = 1$; $\lambda = 0$) indicates total (complete) belief and lack of disbelief; so *p* can be read as a true proposition; ($\mu = 0$; $\lambda = 1$) indicates lack of belief and total disbelief; so *p* can be read as a false proposition; ($\mu = 1$; $\lambda = 1$) represents totally inconsistent believes; so *p* can be read as a contradictory proposition, and ($\mu = 0$; $\lambda = 0$) indicates total absence of belief and disbelief in *p* (logical state called paracomplete or absence of information). Finally ($\mu = 0.5$; $\lambda = 0.5$) indicates that the degrees of belief and of disbelief in *p* are equals, and in this case, *p* can be read as an indefinite proposition.

The consideration of the values of μ and λ is made by specialists who may use their knowledge, probability or statistics. In this work μ is defined as expert's "budget" (taken in this work with $0 \leq \mu \leq 1$) for the case of ESI 2005 and λ as its complement. For example, in Table 1, expert #1 the highest budget was 7 (for natural resource management). This value was attributed to maximum belief ($\mu = 1$). Thus the budget of 3 for air quality (in an interval from 0 to 100 budget), the belief attributed was 3/7 (0.43). To this expert a value of $\lambda = 0.57$ was assigned to the same indicator.

3.3. Logic operators

To set specialists opinions accordingly to the values of μ and λ, one may classify the type of specialist consulted using paraconsistent annotated logic operators (OR, AND). Experts consulted may come from diverse groups of society. Some of them may represent groups, who may give more importance to environmental policies than to the specific quality of water. Others, on the contrary may value biodiversity and give less importance to private sector responsiveness.

Operator OR has the same function of the classical disjunction (maximization). It will be enough for the analysis if one of the expert's opinions is favorable and the result can be considered satisfactory. Operator AND has the same function as the classical conjunction (minimization). In this case, all experts must present favorable opinion to the analysis result satisfactory.

Usually, when the analysis of a real situation is designed, one separates specialists in groups of importance or expertise. OR operator applies intra-groups and the AND operator is to be applied between different groups (inter-groups). Therefore, one can obtain the combined conclusion of the specialist's opinions. For example, if among the 6 experts chosen to weight the ESI's indicators there were 4 specialists on water quality and 2 specialists on air quality, the assessment would be performed maximizing opinions intra-groups and minimizing opinions inter-groups. However, due to the

Table 1
Expert group rates for ESI 2005 indicators, ranked by experts' total budget. White area shows the top seven most rated, light grey area the following seven most rated and the dark grey area the seven indicators with minor budget.

	Indicator	Experts #																	Total	Average ± 2 (1.6)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17		
1st	Air quality	3	5	9	14	4	2	3	5	3	2	5	10	6	6	7	5	10	99	6 (5.8)
2nd	Biodiversity	5	9	7	14	5	5	2	5	3	10	5	5	6	5	6	5	2	99	6 (5.8)
3rd	Water quality	5	5	9	14	6	2	3	5	3	1	5	10	2	4	7	5	10	96	6 (5.6)
4th	Reducing air pollution	6	5	5	2	5	7	8	4	3	10	5	10	5	5	6	5	5	96	6 (5,6)
5th	Land	5	9	6	14	5	2	4	6	11	2	5	5	2	4	4	5	3	92	5 (5.4)
6th	Reducing waste and consumption pressure	6	5	5	2	6	5	8	5	3	5	5	10	8	5	5	5	3	91	5 (5.4)
7th	Reducing ecosystem stresses	6	5	6	2	5	5	6	6	3	2	5	10	8	5	5	4	7	90	5 (5.3)
8th	Environmental health	5	9	4	2	6	5	5	6	3	5	3	5	5	6	6	8	2	85	5 (5.0)
9th	Green house gas emissions	4	2	3	1	6	9	7	5	3	1	5	10	8	6	5	4	5	84	5 (4.9)
10th	Reducing water stress	6	5	4	2	6	7	5	5	3	10	5	3	2	5	6	5	3	82	5 (4.8)
11th	Basic human sustenance	5	5	4	2	5	5	5	6	11	5	3	5	2	4	5	5	5	82	5 (4.8)
12th	Science and technology	3	5	5	0	5	5	6	3	11	5	7	5	2	6	4	5	3	80	5 (4.7)
13th	Water quantity	5	2	5	2	4	7	4	6	3	10	5	5	2	3	6	5	4	78	5 (4.6)
14th	Environmental governance	3	3	3	2	4	5	4	1	14	3	6	1	1	5	4	6	12	77	5 (4.5)
15th	Eco-efficiency	4	2	3	2	4	5	2	5	11	2	5	5	8	5	5	5	2	75	4 (4,4)
16th	Private sector responsiveness	3	5	3	2	5	5	6	5	3	5	5	1	6	4	6	6	5	75	4 (4.4)
17th	Reducing population growth	4	5	7	2	6	5	8	6	3	2	5	1	6	5	5	2	1	73	4 (4.3)
18th	Reducing transboundary environmental pressure	6	5	3	6	4	0	6	5	3	2	5	1	8	4	4	4	5	71	4 (4.2)
19th	Natural resource management	7	9	6	2	4	7	0	6	5	5	5	0	2	0	0	5	3	66	4 (3.9)
20th	Participation in international collaborative efforts	4	2	3	0	4	4	4	2	3	2	5	1	4	5	5	4	7	59	4 (3.5)
21st	Reducing environment-related natural disaster vulnerability	5	0	5	4	6	7	0	4	0	2	3	0	5	0	0	4	4	49	3 (2.9)

lack of information on experts' composition, the analysis was performed in two ways:

(a) Considering both extremes of one single group of specialists: maximizing and minimizing the value of expert's opinions. Fig. 2A shows the case of OR operator use.
(b) Separating three groups of experts through their higher budgets in state-type experts (S), pressure-type experts (P), and response-type experts (R) (Table 2). Fig. 2B shows the case of OR/AND operators.

The classification of experts by type was carried out by accounting the number of indicators with budgets higher than 5 (5 excluded) for each of the 17 experts. When the number of higher budgets for two or more components was the same, the sum of the budgets was used to choose the expert-type (Table 2). The use of three groups of experts intends to attenuate one of the major problems of ESI 2005. The indices represent the sum of 21 indicators of state–pressure–response equally weighted, but it is clear that there is a feedback relation between pressures applied to the system and the state of the system. Also there must be a feedback between the state of the system and policy responses, and finally between policy responses and the pressures. In this way, experts' opinions on what is more important to evaluate the sustainability of countries may include personal interpretations of these feedbacks. For example, one expert may give a high budget for eco-efficiency indicator assuming the benefits associated to the reduction of air pollution or the improvement of water quality.

3.4. Graphical analysis

The Cartesian product $[0;1] \times [0;1]$ of all annotation pairs (μ,λ) determines the Cartesian Unitary Square shown in Fig. 3, and important features as the uncertainty degree, $U_D(\mu,\lambda) = (\mu + \lambda - 1)$ and the certainty degree, $C_D(\mu,\lambda) = (\mu - \lambda)$, can be considered. The limit region ABCD is defined in Fig. 3 by $|U_D| = 0.5$ and $|C_D| = 0.5$, and called level of requirement. When a point that translates the analysis is located within this region, the analysis is non-conclusive.

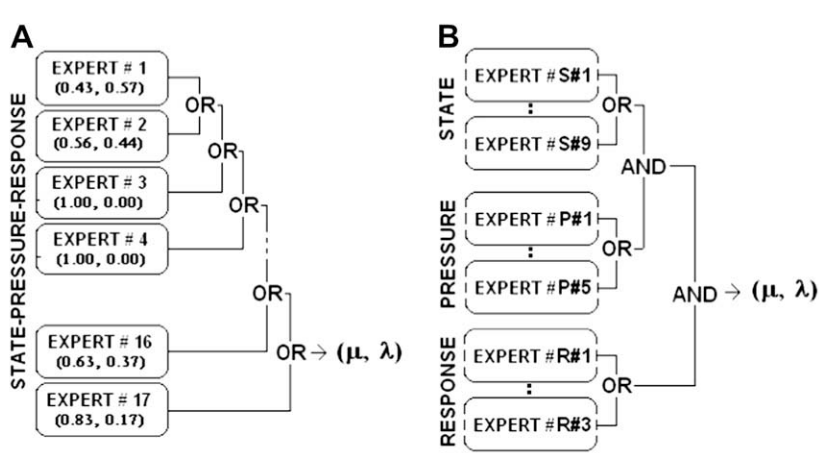

Fig. 2. Schematic representation of the use of logic operators. (A) The case in which is not possible to separate experts by type, as used in this work and (B) the case in which is possible to classify experts by type. Note that accordingly to Table 2 there are 9 state-type experts, 5 pressure-type experts and 3 response type experts.

Table 2
Number of higher budgets (>5) given by experts to the ESI components state–pressure–response.

Component	Experts #																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
State	1	4	5	4	3	3	1	4	2	1	–	3	3	3	5	1	2
Pressure	4	–	2	–	4	3	4	2	–	2	–	3	3	–	2	–	1
Response	1	–	–	1	–	–	3	–	3	–	1	–	2	1	1	2	2
Expert-type	P	S	S	S	P	S	P	S	R	P	R	S	P	S	S	R	S

S (state-type expert), P (pressure-type expert), and R (response-type expert).

It is important to note that the level of requirement determines the responsibility of the analysis, or the degree of caution to use the analysis, which depends on the further use of the results (such as an indicator for investments or for decision making) and its implications. For a level of requirement of 50%, assessments will be carried on with at least 50% of certainty.

The graph can be split into 12 regions of uncertainty and certainty degrees. All the states are represented by the usual Cartesian system in the lattice of Fig. 3. Extreme states are, false (f), true (ν), inconsistent (T) and paracomplete (⊥), and non-extreme states.

3.5. Baricenter determination

For the final analysis, it is possible to combine all analyzed factors, determining the baricenter (W) of the points that represent each expert or indicator separately. The degree of belief (μ) of W is the arithmetic average of the resulting degrees of belief for all the factors, and the degree of disbelief (λ) is the arithmetic average of the resulting degrees of disbelief for the factors (Carvalho, 2002).

For a given proposition p, with μ and λ values of W one can calculate the degree of certainty of the analysis performed. Thus, using the ESI 2005 information, two propositions were made:

$p(\mu,\lambda)$: Experts accept underlying variables and indicators chosen by ESI 2005, that is, an analysis of the consistency/inconsistency of weights is performed.

$P(M,\Lambda)$: Experts' ranking accept the ESI 2005 rank, that is, the implication of weights to the consistency/inconsistency of ESI rank is evaluated.

To examine proposition $p(\mu,\lambda)$, the baricenter determination was first performed considering only data regarding experts' opinions (Section 4.1).Through the application of paraconsistent logic techniques of maximization (OR) and minimization (AND), resultant degrees of belief (μ) and disbelief (λ) for the whole group of experts were obtained. This analysis permits to assess the conflict among experts and differences among experts' weighting and the uniform weighting adopted by ESI 2005.

It is also possible to apply paraconsistent logic techniques of maximization and minimization, to exam proposition $P(M,\Lambda)$ determining degrees of belief (M) and disbelief (Λ) for each one of the 21 indicators, accordingly to experts weighting (Section 4.2). Indicators plotted on the Cartesian Unitary Square enable to find out how indicators (formerly aggregated with uniform weighting) were influenced by expert's budget. The baricenter will locate each

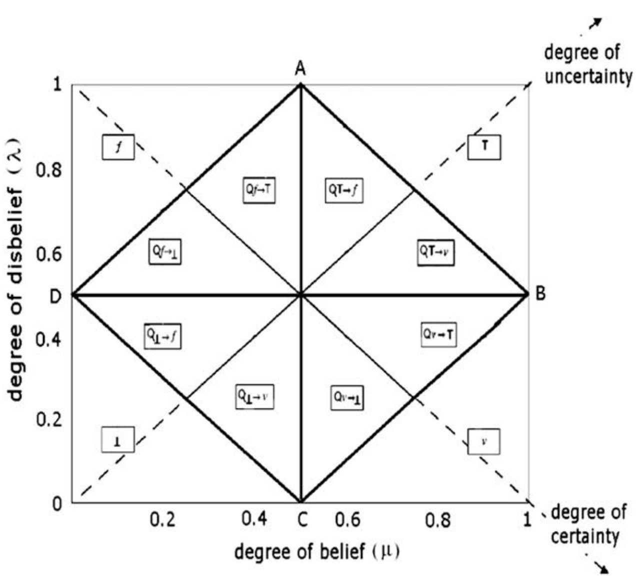

Fig. 3. Cartesian Unitary Square divided into 12 regions as follows: f (false), T (inconsistent), ν (true), and ⊥ (paracomplete), Qf → ⊥ (Quasi-false tending to paracomplete), Q⊥ → f (Quasi-paracomplete tending to false), Qf → T (Quasi-false tending to inconsistent), Q⊥ → ν (Quasi-paracomplete tending to true), QT → f (Quasi-inconsistent tending to false), Qν → ⊥ (Quasi-true tending to paracomplete), QT → ν (Quasi-inconsistent tending to true), and Qν → T (Quasi-true tending to inconsistent).

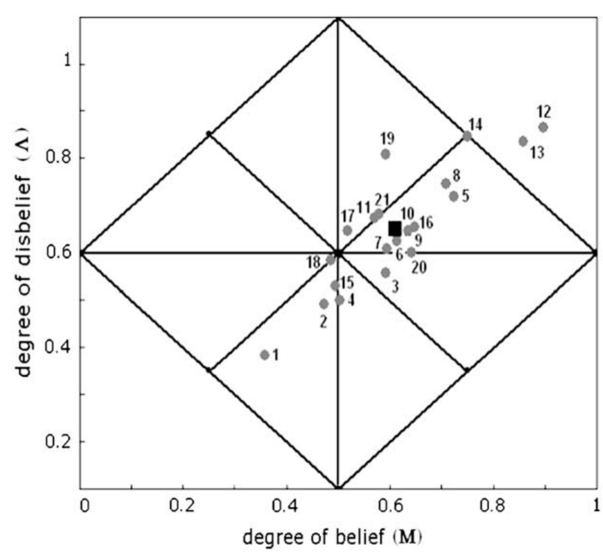

Fig. 4. Cartesian Unitary Square for Brazilian indicators and the respective baricenter (■). In this case, only maximization technique was employed. Indicators are identified as 1 (air quality), 2 (biodiversity), 3 (land), 4 (water quality), 5 (water quantity), 6 (reducing air pollution), 7 (reducing ecosystem stresses), 8 (reducing population growth), 9 (reducing waste and consumption pressure), 10 (reducing water stress), 11 (environmental governance), 12 (green house gas emissions), 13 (basic human sustenance), 14 (reducing environment-related natural disaster vulnerability), 15 (natural resource management), 16 (eco-efficiency), 17 (private sector responsiveness), 18 (science and technology), 19 (participation in international collaborative efforts), 20 (environmental health) and 21 (reducing transboundary environmental pressure).

country of the ESI 2005 rank on the Cartesian Unitary Square, and the analysis will permit to compare the ESI 2005 rank with that obtained using paraconsistent logic. The example in Fig. 4 shows the Cartesian Unitary Square for Brazilian indicators, with the baricenter W (0.61, 0.55). With M and Λ values of W one can also calculate the degree of certainty of the analysis performed in all countries of the ESI 2005 rank.

4. Results and discussion

4.1. Examining proposition p (μ,λ)

4.1.1. Experts' opinions accept the underlying variables and indicators chosen by ESI 2005

The expert rating of ESI indicators was obtained by averaging the opinion from 17 experts working on a broad spectrum of environmental sustainability and policy issues. Table 1 shows the 21 indicators averaged with relative importance between (3 ± 2) and (6 ± 2), for a confidence interval of about 70%. It is worthy to note that weights given to each indicator are quite different. For example, for air quality indicator, "budgets" vary from 2 to 14, and for environmental governance indicator they vary from 1 to 14. There are also indicators with a zero budget.

Fig. 5 shows the Cartesian Unit Square for the experts' opinions on the 21 indicators, by averaging the opinion from 17 experts as it was used by ESI 2005. Note that, the use of average values turns the analysis to the Aristotelian logic, which divides the Cartesian Unit Square in two regions: true (white region) and false (grey region). This preliminary analysis shows the baricenter, W (0.6, 0.4), with a certainty degree of 18%. It is also worthy of attention that, even using average values for experts' opinions, three of the 21 indicators – natural resource management (19th in Table 1), Participation in international collaborative efforts (20th in Table 1) and reducing environmental related natural disaster vulnerability (21st in Table 1) – are located in the false region, and should not be used to compose the index, accordingly to evaluation of the experts.

When specialists' opinions are analyzed with paraconsistent annotated logic, it becomes clear that experts do not agree at all

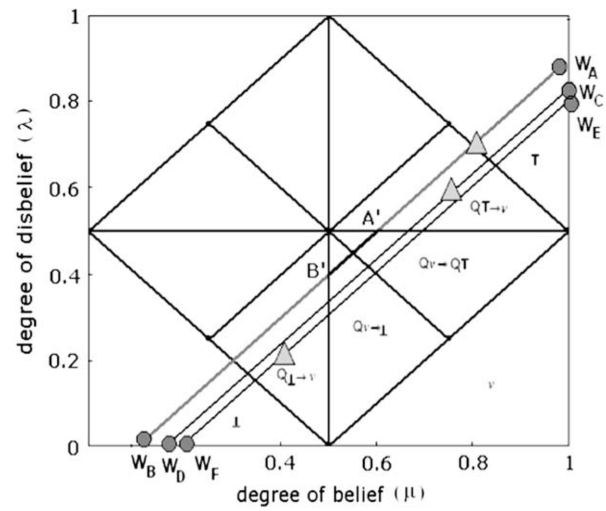

Fig. 6. Cartesian Unitary Square considering the 21 indicators (W_A W_B), considering the top 14 ranked indicators (W_C W_D) and the top 7 ranked indicators (W_E W_F). Where: T (inconsistent), $\perp$ (paracomplete), $Q\perp \rightarrow v$ (Quasi-paracomplete tending to true), $Qv \rightarrow \perp$ (Quasi-true tending to paracomplete), $QT \rightarrow v$ (Quasi-inconsistent tending to true), and $Qv \rightarrow T$ (Quasi-true tending to inconsistent). Straight lines show maximization data. Triangles show the baricenters obtained when the analysis is performed separating three experts' groups. For $\mu = 0.98$ and $\lambda = 0.88$, $C_D = \mu - l = 0.1$ and $U_D = \mu + \lambda - 1 = 0.86$.

(Fig. 6). W_A represents the baricenter of all 21 indicators when expert's opinions are maximized and point W_B the baricenter obtained when their opinions are minimized. The straight line W_AW_B shows that all possible combinations of the expert's opinions go through from paracomplete to inconsistent and only the segment $A'B'$ lies in the region Qv (Quasi-true), but tending to paracomplete or inconsistent. The uncertainty degree (U_D) at point W_A is 0.82 and the certainty degree (C_D) equals 0.15. Triangles show the baricenters obtained when the analysis is performed separating three experts' groups.

Fig. 6 shows also two more straight lines. Segment W_CW_D joins the baricenters found when only the top 14 indicators are considered (white and light grey areas in Table 1), and W_EW_F connects the baricenters obtained when only the top 7 indicators are taken into account (white area in Table 1). It is clear that when indicators that had a higher "budget" from all experts are chosen, baricenters shift in direction to the true region (v). However, even taking only one-third of the indicators used by ESI 2005, the result is almost the same, that is, there is no combination of the experts' opinions that may lead to a conclusive analysis, with a level of requirement of 50%.

This result is consistent with criticisms to ESI 2001 found in the literature (Niemeijer, 2002). Such criticisms emphasize that the power of an index does not increase with the number of indicators and variables it covers but with the elimination of superfluous variables. A lesser number of indicators could also increase transparency, because it is easier to understand how a limited number of variables influence a sustainability index than when a large number of variables are concerned.

The position of the baricenter W_A (0.15, 0.82) in the T region indicates totally inconsistent believes among experts. This result suggests that experts need more information to weight properly the proposed indicators and p can be read as a contradictory proposition.

When the analysis is performed using three separate groups of experts, the baricenters obtained lie on the straight lines between maximized and minimized baricenters as expected (Fig. 6), but for this combination of experts, the uncertainty degree (U_D) falls

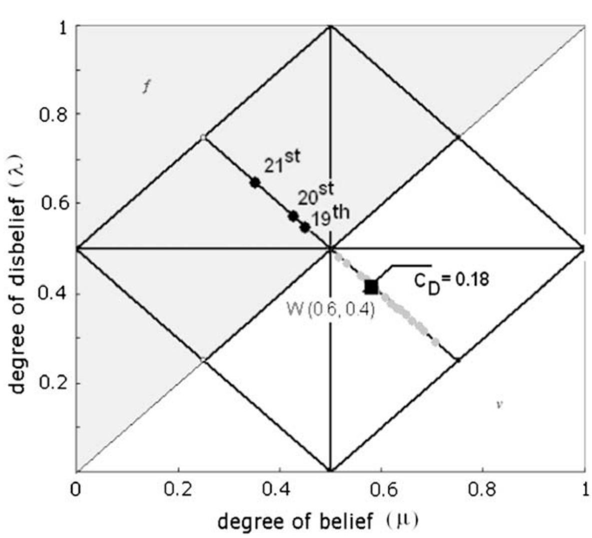

Fig. 5. Cartesian Unitary Square for the average of experts' opinions on the 21 indicators. Grey points show indicators from 1st to 18th places in Table 1. All indicators are in the same axes, as contradictions were not yet considered. Their position shows how far indicators are, in average, from true or false regions.

to 0.46 and the certainty degree (C_D) equals 0.16. Accordingly to this result, the conflict among experts could be attributed to their different views of the environmental issues. The certainty degree of the analysis remains almost the same, but when opinions inter-groups are confronted, the uncertainty of the analysis diminishes.

4.2. Examining proposition P (M,Λ): experts ranking accept ESI 2005 rank

4.2.1. Considering one single group: maximizing the value of experts' opinions, as shown in Fig. 2A

Comparing the ESI rank with that weighted by experts showed some variations. In the ESI 2005 report, the averaged experts' budget brought a pronounced positive effect on the rank of a few countries such as Sri Lanka and Niger, and a negative effect on others such as Chile, South Africa and Italy. The shift on the rank was attributed to the relative importance given to one or more indicators by some experts in disagreement with average value (Esty et al., 2005).

Fig. 7 shows the ESI rank with uniform weighting compared to the rank obtained with paraconsistent annotated logic using only OR operator. In general, the positions in the rank do not vary significantly, but discrepancies are higher than that obtained averaging experts' opinions, as paraconsistent annotated logic evidences the conflict among experts, which was minimized by the averaged budget. Using this analysis, a positive effect was observed for Italy, Sri Lanka and South Africa. Niger presented a negative shift in the rank, and Chile maintained its position.

4.2.2. Separating experts through their higher budgets in state-type experts, pressure-type experts, and response-type experts as shown in Fig. 2B

Fig. 8 shows the ESI rank with uniform weighting compared to the rank obtained with paraconsistent annotated logic separating experts by their preferences. The positions in all three ranks obtained do not vary, in relation to that obtained maximizing all experts' opinions (OR operator), but discrepancies related to that obtained averaging experts' opinions are lower.

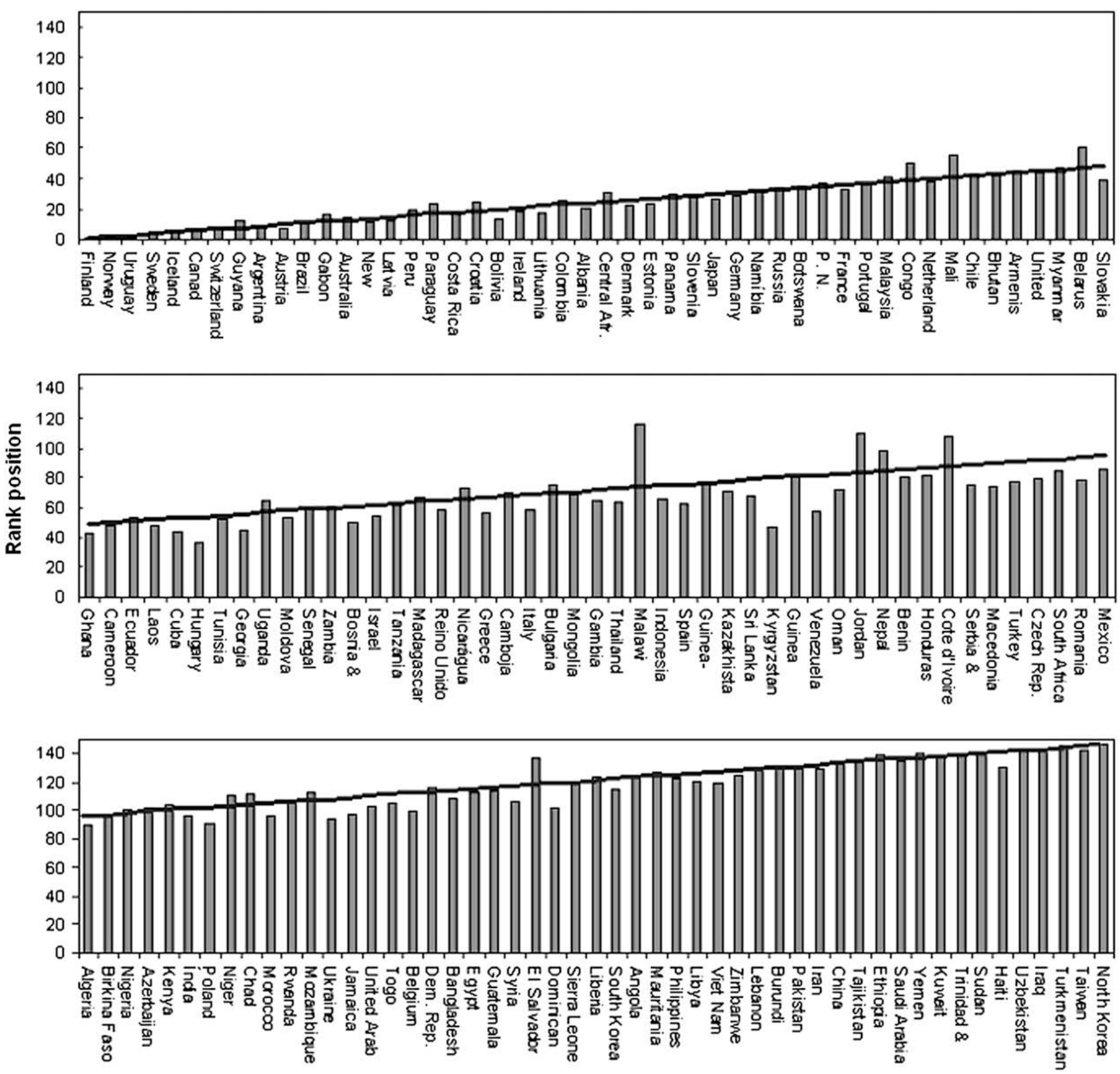

Fig. 7. ESI 2005 ranking (straight line) with uniform weighting versus paraconsistent annotated logic ranking (bars) without experts' classification.

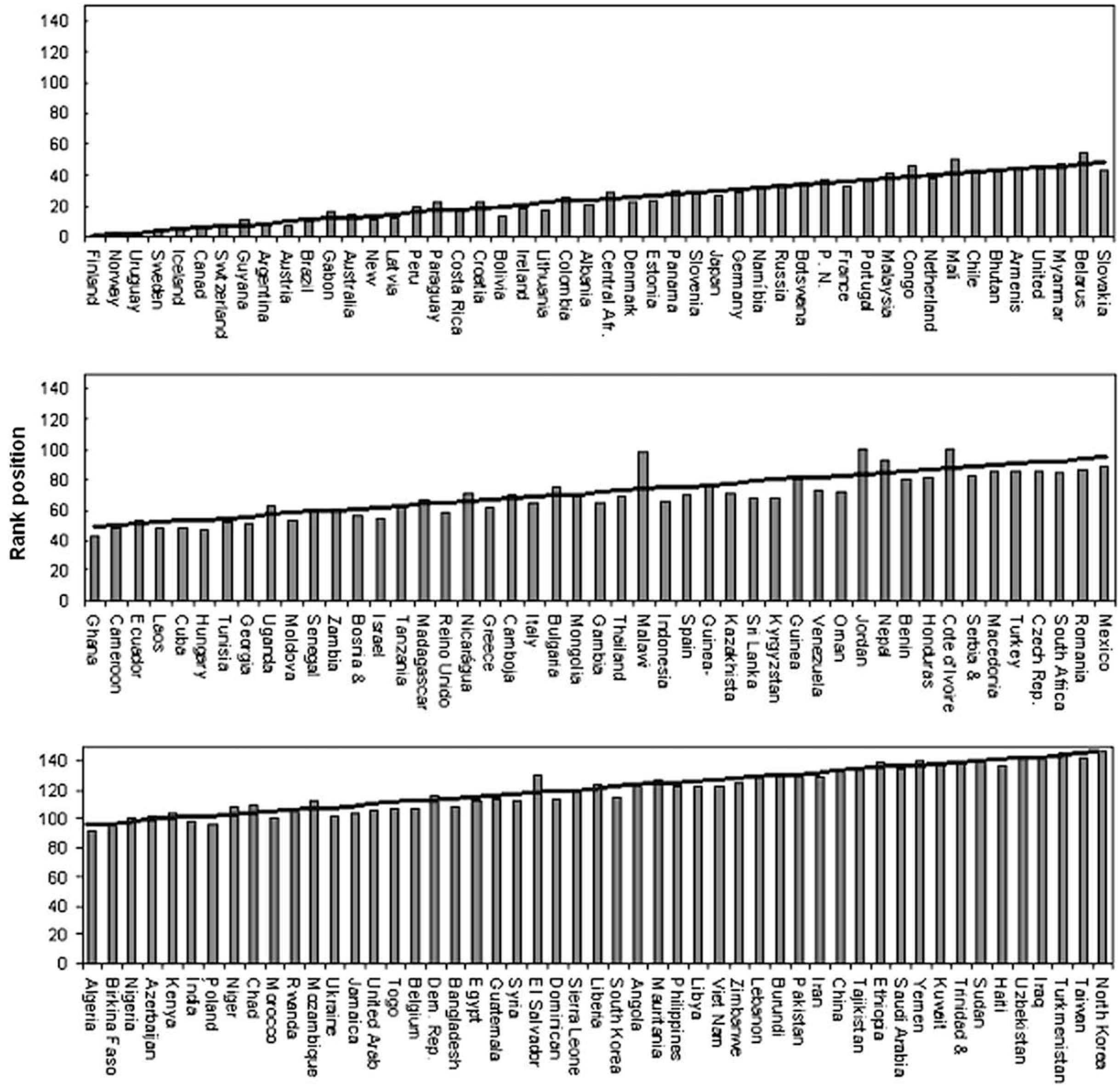

Fig. 8. ESI 2005 ranking (straight line) with uniform weighting versus paraconsistent annotated logic ranking (bars) separating experts by type (state-type experts OR pressure-type experts AND response-type experts).

4.3. The influence of characteristic data of each country

When the weighting based on experts' opinions is confronted to data of each country, it can be noted that the points representing the indicators with higher "budget" are closer to the straight line W_AW_B, which represent experts' opinions (Fig. 9). As the baricenter W is the arithmetic average of the resulting degrees of belief for all the factors, it shifts far from the W_AW_B segment, due to the use of indicators that had minor budget (grey points in Fig. 9). Thus, it may be inferred that, accordingly to the opinion of those 17 experts, the indicators listed after the 13th place in Table 1 should not be used to calculate the ESI 2005 for Brazil.

When the weighting based on experts' opinions is taken into account to rank the countries by ESI 2005, the results are similar. Fig. 10 shows the results obtained for Finland, Bulgaria and Sudan. Finland occupies the first position in the ESI 2005 rank, Bulgaria is in the 70th place and Sudan is the 140th.

To a level of requirement of 50%, for Finland ($M = 0.57$; $\Lambda = 0.49$), the baricenter lies in the region QT → v (Quasi-inconsistent tending to true), Bulgaria ($M = 0.44$; $\Lambda = 0.39$) and Sudan ($M = 0.39$; $\Lambda = 0.32$) in the region Q⊥ → v (Quasi-paracomplete tending to true).

The position of baricenters of each country shows that, the higher in rank is the country, the more its baricenter approaches the inconsistency region. This result indicates that experts disagree on the choice of variables/indicators, and need more information to accept and weight the indicators offered by ESI 2005. On the other hand, Sudan's baricenter is close to the paracomplete region, which suggests that data supplied by the country were insufficient. For all countries there are also indicators positioned within the inconsistency and the paracomplete regions, which should no be used in a strict analysis.

The analysis of all countries present a certainty degree of 0.15 and $U_D = 0.82$ considering one group of experts. For experts separated in three groups the certainty degree equals 0.16 (Fig. 11) and the uncertainty degree decreases, $U_D = 0.46$. A shift of all countries

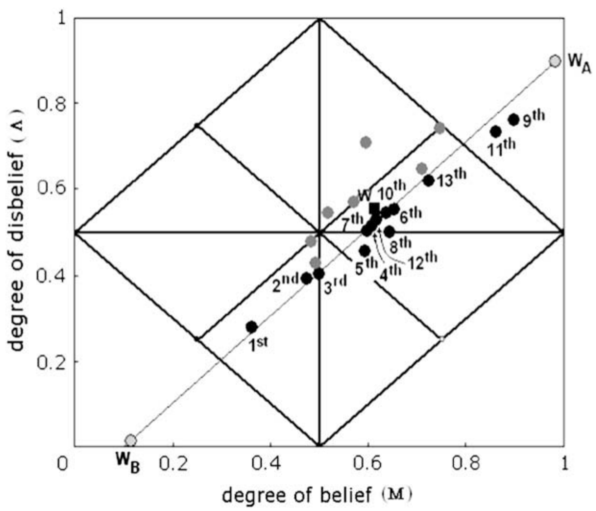

Fig. 9. Cartesian Unitary Square for Brazilian indicators and the respective baricenter W (■). Indicators are identified as their position in Table 1.

in direction to the paracomplete region is observed, but their relative positions remain the same. All other countries in the rank have their baricenters on the straight line shown in Fig. 11 between Finland (F) and North Korea (NK), the 146th ranked. This result shows that, based on experts' opinions, one may place Finland as the first in the rank with only 15% of certainty, which fulfills a very low level of requirement (<20%). As the ESI was constructed to draw attention to the actual environmental conditions of the countries ranked and to offer a guide for decision making, it is worthy to note that a degree of certainty of 16% gives a weak basis for this assignment.

5. Concluding remarks

Governments are concerned about the quality of their environmental resources, and decision makers need reliable support on the effects of the management options they eventually consider. CEIs intend to offer a limited set of indicators to recognize effectively environmental issues, to monitor environmental conditions efficiently and to measure decisions results. In this way, a CEI could presumably be a tool in environmental debate and, in the future, such a measure would have potential for seriously impacting domestic and international policy analysis. Hence, there must be widespread acceptance of the CEI's structure and methodology.

In the present, the construction of most CEIs passes through a theoretical step, when environmental experts are involved for the purpose of selecting and classifying the most representative variables and/or indicators that form CEIs' basis (Yuan et al., 2003; Esty et al., 2005).

In general, "opinions" are not expected to be consistent, as experts come from quite different sectors (academic, governmental, business, non-governmental, etc) and have different expertise. On the other hand, decision-making has become increasingly data-driven, and environmental issues have gone too slow in this regard. Hence, because of the complexity of environmental data sets, in particular, with regard to the ecosystem functioning, there are widespread information gaps and uncertainties, and environmental decisions and policies are frequently dependent on general observations, experts' opinions and even in green slogans.

One step of CEIs construction depends directly on experts' opinions, since experts must, at least, chose the underlying

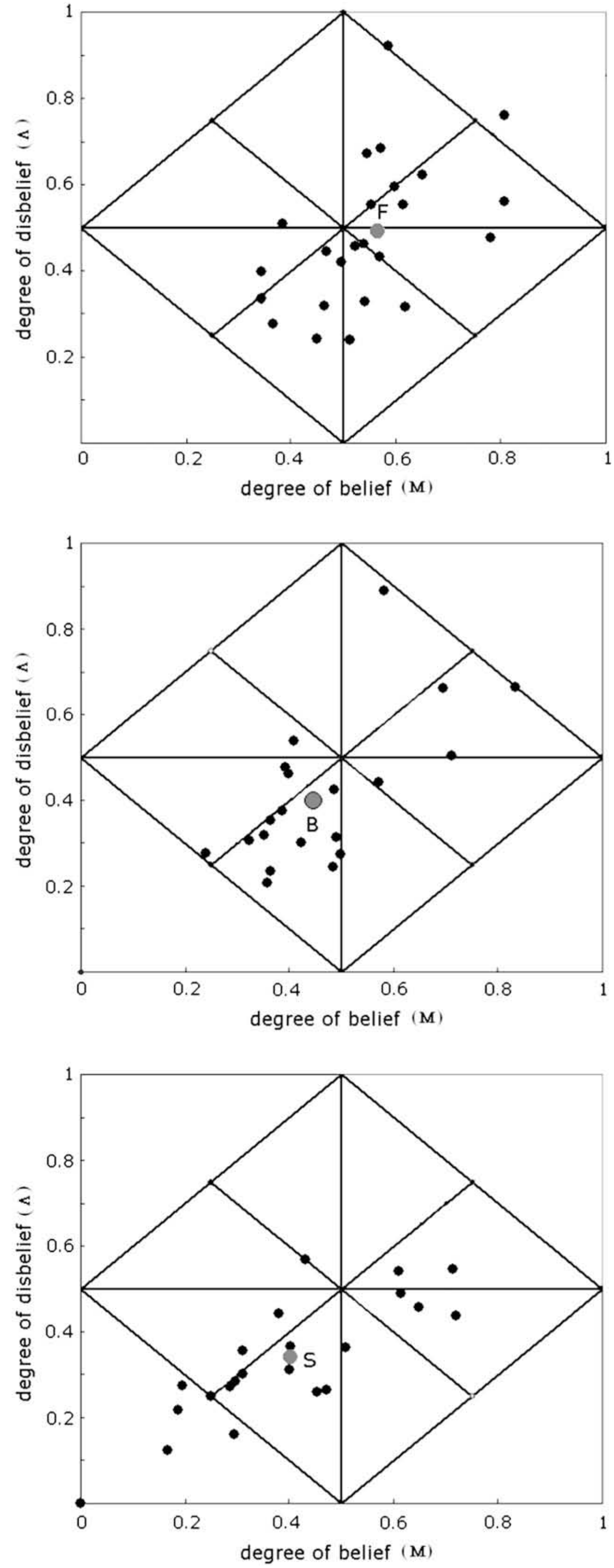

Fig. 10. Cartesian Unitary Squares for Finland (F), Bulgaria (B) and Sudan (S). Baricenters were obtained separating three experts' groups.

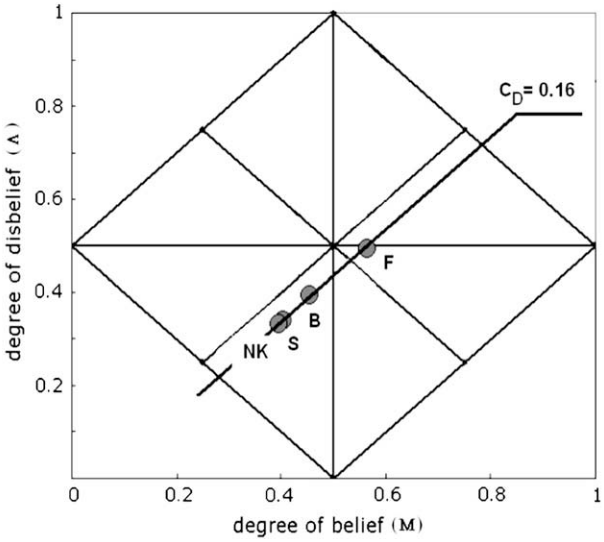

Fig. 11. Cartesian Unitary Square for Finland (F), Bulgaria (B), Sudan (S) and North Korea (NK), and the certainty degree of the analysis, considering three groups of experts.

variables that compose the index. On the other hand, CEIs are built with the idea that effective decision making requires complex environmental systems to be captured in one or more simple indicators (understandable to decision makers in a way similar to the GDP, Gross Domestic Product), but for this, uncertainties related to the selection of variables and/or indicators must be avoided.

Literature is well-fed with calls for CEIs as tools for the measurement of progress towards sustainability. Some of them, as ESI 2005, are organized into cause–effect (i.e. pressure–state–response) models, and experts vary a great deal on what is the most suitable group of indicators to create a list and do the monitoring. Some favor a 'top-down' or technocratic process with specialists setting the underlying variables composing the selected indicators. Others favor a 'bottom up' style with the participation from stakeholders or governments who will be affected by the application of the CEIs. Both situations were simulated in this study: the ESI 2005 uniform weighting represents the technocratic process and the use of experts' budget the 'bottom up' style. Hence, despite of the search for indicators to represent a real measure of sustainability, there are still some questions to be responded by the academic community:

1. What indicators will be used to measure progress towards sustainable development?
2. Who will select those indicators?
3. How will they be measured?
4. What will be the limit for their use?

As it was shown using paraconsistent annotated logic, environmental experts assigned to select the most representative of the indicators composing the ESI 2005 did not agree on the relative importance of one among others. Experts, despite of their specific knowledge in their own area, feel a lack of sureness, confidence or knowledge when making opinion on different subjects, and individual judgment is used. Their weighting for environmental indicators, which possibly included appraisals held without scientific proof, may compromise the objectiveness of the analysis. It is reasonable to infer that a group formed by the same experts would have difficulties in the choice of indicators for constructing a CEI.

The uncertainty due to the disagreement in experts' opinions clearly denotes the lack of a "science of sustainability". At this moment, there are countless definitions of "sustainability" and numerous indicators that propose to measure some kind of sustainability. Then, a central issue is the construction of a scientific basis for dealing with this relatively new concept.

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Appendix. Paraconsistent annotated logic for analyzing ESI 2005

Determining μ and λ

During the procedure that employs different expert's opinions in constructing a CEI (composite environmental index), a major difficulty is to select the proper variables and the weight of each variable in relation to other chosen parameters. Experts choose these variables based on a multitude of influencing factors. As a consequence, choices may be based on sparsely catalogued data, mainly supported on the experience and sensitivity of the expert responsible for making the selection. In this case, paraconsistent annotated logic may be a useful tool to conciliate expert's opinions.

Section 4.1 of the main text presents the analysis of the proposition $p(\mu,\lambda)$, which can be intuitively read: "It is assumed that p's belief degree (or favorable evidence) is μ and disbelief degree (or contrary evidence) is λ."

For ESI 2005: "It is assumed that experts accept underlying variables and indicators chosen" leads to $\mu = 1$ and "It is assumed that experts do not accept underlying variables and indicators chosen" leads to $\lambda = 1$.

For applying paraconsistent annotated logic to ESI 2005 expert's budgets, the values given by the experts were converted into μ values, defining the highest budget of each experts as equivalent to total belief ($\mu = 1$) to fit the closed real interval [0;1]. Values for λ were defined as $(1 - \mu)$. The results for Expert #1, for example, are shown in Table A1.

Table A1
Values of the degree of belief and disbelief for Expert #1 from the budget presented in ESI 2005. ESI indicators are identified by the ordinal numbers shown in Table 1 in the main text.

Indicator	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th	13th	14th	15th	16th	17th	18th	19th	20th	21st
Budget	3	5	5	6	5	6	6	5	4	5	5	3	5	3	4	3	4	6	7	4	5
μ	0.4	0.7	0.7	0.9	0.7	0.9	0.9	0.7	0.6	0.7	0.7	0.4	0.7	0.4	0.6	0.4	0.6	0.9	1.0	0.6	0.7
λ	0.6	0.3	0.3	0.1	0.3	0.1	0.1	0.3	0.4	0.3	0.3	0.6	0.3	0.6	0.4	0.6	0.4	0.1	0.0	0.4	0.3

With values of μ and λ settled, the analysis can be carried out using operators OR and AND.

Operator OR has the function of maximization, and was applied for the case in which experts' specialties are not well defined (see Fig. 2 in the main text). This operator is defined by: (μ_1,λ_1) OR $(\mu_2,\lambda_2) = (\max\{\mu_1,\mu_2\};\ \max\{\lambda_1,\lambda_2\})$. For Expert #1 $(\max\{\mu_1,\mu_2\};\ \max\{\lambda_1,\lambda_2\}) = (1.0, 0.6)$. The certainty degree of the analysis can be defined by Eq. (A1).

$$\max\{\mu_1,\mu_2\} - \max\{\lambda_1,\lambda_2\} \tag{A1}$$

Thus for Expert #1, the certainty degree equals 0.4.

$$\max\{\mu_1,\mu_2\} + \max\{\lambda_1,\lambda_2\} - 1 \tag{A2}$$

The uncertainty degree is defined by Eq. (A2), and for Expert #1 it corresponds to 0.6.

Operator AND has the function of minimization, and was applied for the case in which experts' specialties were defined (see Fig. 2 and Table 2 in the main text).

Operator AND is defined by: (μ_1,λ_1) AND $(\mu_2,\lambda_2) = (\min\{\mu_1,\mu_2\};\ \min\{\lambda_1,\lambda_2\})$. For Expert #1 $(\min\{\mu_1,\mu_2\};\ \min\{\lambda_1,\lambda_2\}) = (0.4, 0.0)$. The certainty degree of the analysis is defined by Eq. (A3), and for Expert #1, the certainty degree equals 0.4.

$$\min\{\mu_1,\mu_2\} - \min\{\lambda_1,\lambda_2\} \tag{A3}$$

The uncertainty degree is defined by Eq. (A4), and for Expert #1 it corresponds to 0.6.

$$\min\{\mu_1,\mu_2\} + \min\{\lambda_1,\lambda_2\} - 1 \tag{A4}$$

Since the annotation pairs for each indicator (μ,λ) were defined, and the Uncertainty Degree and the Certainty Degree were calculated, results can be shown in the Cartesian Unitary Square. Then, the baricenter (W) of the points, that represents the arithmetic average of the resulting degrees of belief for all experts' opinions, can be determined (see Fig. 4 in the main text).

Determining M and Λ

The raw data to define ESI 2005 indicators values were taken from Appendix B of ESI 2005 main report (Esty et al., 2005), in which the value of each indicator is shown for the 146 countries evaluated. Each indicator builds on between 2 and 12 data sets for a total of 76 underlying variables. Air quality, for example, is a composite indicator that includes variables tracking the concentration of nitrogen oxides, sulfur dioxide, and particulates. For analysis using paraconsistent annotated logic, the values of each one of the 21 indicators was adjusted in order to fit the closed real interval [0;1], as ESI 2005 weighted summations, in the form of averages, are not scale invariant.

The ESI 2005 rank is constructed on the summation of the values of the five aggregated components, which are composed of the 21 indicators. In this way, for each component, the highest and the lowest values were used to fit each ESI indicator in the [0;1] interval (Eq. (A5)).

$$\text{ESI 2005 indicator} = \frac{(\text{ESI 2005 value}) - (\text{component's lowest value})}{(\text{component's highest value}) - (\text{component's lowest value})} \tag{A5}$$

For example, in the case of the component reducing stress, the highest value for Albania is 1.82 and the lowest value is −2.49. Then, each indicator taken from the Albania's data set (Esty et al., 2005), used to compose the reducing stress component was normalized according to Eq. (A6).

$$\text{Reducing air pollution}_{\text{Albania}} = \frac{(0.42) - (-2.49)}{(1.82) - (-2.49)} \tag{A6}$$

For the analysis of proposition P (see Section 4.2 in the main text), which denotes a propositional variable, $p\ (M,\Lambda)$, values of μ and λ of each expert were multiplied by their correspondent value in the ESI 2005 scale, already fitted to the [0;1] interval (see example in Table A2).

Table A2
Example of M and Λ calculation for Albania including the ESI 2005 indicators.

	Indicator	μ_{max}[a]	λ_{max}[a]	ESI 2005 indicator	M[b]	Λ[b]
1st	Air quality	0.4	0.6	0.54	0.22	0.32
2nd	Biodiversity	0.7	0.3	0.49	0.34	0.15
3rd	Water quality	0.7	0.3	0.46	0.32	0.14
4th	Reducing air pollution	0.9	0.1	0.68	0.61	0.07
…	…	–	–	–	–	–
21st	Reducing environment-related natural disaster vulnerability	0.7	0.3	0.38	0.27	0.11

[a] $(\max\{\mu_1,\mu_2\};\ \max\{\lambda_1,\lambda_2\})$ for each indicator considering the budget of all 17 experts with operator OR.
[b] $(\max\{\mu_1,\mu_2\} \times \text{ESI 2005 indicator};\ \max\{\lambda_1,\lambda_2\} \times \text{ESI 2005 indicator}) = (M,\Lambda)$.

Ranking the countries with paraconsistent annotated logic results

The rank constructed from paraconsistent annotated logic results used the degree of belief of each country baricenter.

For each country, the baricenter W was calculated by the arithmetic average of the resulting degrees of belief for all experts' opinions multiplied by the values of each ESI 2005 indicator (Table A2).

The new rankings including experts' opinions show the obtained results for the case in which experts' classification is not clear or possible (Fig. 7 in the main text) and for the case in which experts were separated by type (Fig. 8 in the main text). For the location of each country in the Cartesian Unitary Square, the annotated pairs of the composite environmental index baricenter for each country was calculated by the arithmetic average of M_{max} and Λ_{max} of the 21 indicators.

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