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A framework towards a composite indicator for urban ecosystem services

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ABSTRACT

This article describes a composite indicator for ecosystem services. This composite is composed of several sub-indices, each representing either land use types or ecosystem services. While the overall composite indicates a general overview of the performance of a system in terms of ecosystem services provision, the sub-indices provide sources of variation. Taking into consideration potential trade-offs between making the framework complex and keeping it simple, the composite was developed on two levels. The first level, a simpler one, requires few indicators and therefore needs less data as inputs. The second level, in contrast, is more complex requiring more indicators, involving more detailed measurements, and therefore can be applied with more confidence.

1. Introduction

Ecosystem services (ES) is a multi-dimensional concept that combines a large number of ecological, biophysical and social values (MEA, 2005). There is an increasing demand for a comprehensive composite indicator for measuring and evaluating ES, since the high degree of information needed for traditional measurements are often not available and collection of biophysical and economic data is often resource intensive. In view of this growing demand, a new composite indicator – Ecosystem Services Composite (ESC) – is proposed and described in this article.

The use of indicators for environmental monitoring is not new and they have been successfully utilized for environmental policy and planning for some time (de Sherbinin et al., 2013). A composite indicator (often called an "index") is formed by combining together a few or many individual indicators. It is then used to understand the dynamics of a system in a single numerical value. Among numerous successful composite indicators are Environmental Performance Index (Hsu et al., 2013), Ocean Health Index (Halpern et al., 2012) and Human Development Index (UNDP, 2014), each being applied at different scales targeting different sectors. Whatever their scale or the sector of application, their underlying structure, methodology and theoretical considerations have certain similarities.

The aim of this article is to present a newly developed ecosystem services composite, to describe its various components and to show an application using a prototype. The article begins with a discussion on the need for a composite of ES and its potential applications in research and policy making. Next, we provide a broad conceptual framework followed with a description of five major methodological steps. We then present a case study of a Canadian city where this tool is being tested. Finally, we discuss some of the pros and cons as well as on the opportunities for improvements in a more complex situation.

2. Why a composite indicator for ecosystem services?

One of the outstanding research questions in ecology and ecological economics today is the relationship between ecosystem structure, processes and ecosystem services (Daily et al., 2009; Kandziora et al., 2013; Mitchell et al., 2013). How can the provision of ES be linked to biodiversity and ecosystem dynamics? How a marginal change in forest area may change ES and how these marginal values are to be quantified in a meaningful way?

There is a large body of literature on economic valuation from across the continents (TEEB, 2010). While economic value generates useful information regarding the extent and magnitude of many ES, it has limitations in 'aggregation' of a bundle of services. This is partly because of the issues related to valuation of cultural services (e.g. recreational, religious and educational services), since

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they have no market in conventional sense (Daniel et al., 2012). There are arguments that cultural ES are non-material in nature, therefore cannot be aggregated or traded-off with material services. Contrary to this, Satz et al. (2013) argue that despite the incommensurability between material and non-material services, it may be possible to compare them and even make trade-offs. Such incommensurability can be dissolved either by expressing them in the same units (e.g. monetary value) or transforming them into dimensionless values. A composite indicator works to resolve such issues arising from multiple dimensions of different variables (de Sherbinin et al., 2013; Nardo et al., 2005).

Other potential applications of the composite can be achieved by integrating it into spatial analyses. Although widely used in spatial modelling, land use and land cover (LULC) is probably a poor proxy of ES supply (Eigenbrod et al., 2010). The composite can overcome this shortcoming. Mapping ESC values can reveal important information regarding supply and use of ES. Such spatially explicit information may also help mainstream ES framework into long-term planning and policy processes (Maes et al., 2012). These mapping exercises will also lead to answering outstanding research questions such as: biodiversity-ES spatial congruence (Anderson et al., 2009), trade-offs (Mace et al., 2012) and demand-supply gap analysis (Burkhard et al., 2012).

3. Conceptual framework

The multivariate concept of ES is often explained in terms of ecological, physical, social and economic indicators. These indicators individually do not convey meaningful information until they are analyzed altogether. The idea behind the composite is to combine those multi-dimensional concepts and variables into a single value. Mathematically it can be represented as:

$$ESC = \frac{\sum_{i=1}^{n} X_i w_i}{N}$$

Subject to,

$$\sum_{i=1}^{n} w_i = 1 \text{ and } 0 \leq w_i \leq 1$$

where, X_i, normalized variables, w_i, weight of X_i, and N, number of sub-indices

The theoretical foundation of the composite is similar to that of existing environmental indices such as City Biodiversity Index (Chan et al., 2014). However, like any other indices the ESC has strengths in some areas and weaknesses in others; Table 1 lists some of them.

Taking into consideration the potential trade-offs between making the framework complex and keeping it simple, the ESC was developed at 2 levels. Level-1 framework is simpler, requires few indicators, and therefore needs less data as inputs. Level-2, on the other hand, is a more complex one, needs more indicators, involves more measurements, and therefore can be applied in real world with more confidence. Examples of level-1 indicators for air quality regulation in an urban setting are area of forest, street density and vehicle load; whereas, level-2 indicators include leaf area index (LAI), weather data, pollutant particle concentration and so on (Table 2).

The ESC is composed of several sub-indices, each representing either a land use type or an ecosystem service. While the composite provides an indication of the overall performance of the system, the sub-indices are aimed at a more detailed understanding of the sources of variation within the ESC. Ideally a set of indicators would have to be selected for each ecosystem services right at the beginning. Those indicators will vary depending on land cover characteristics, therefore, sub-indices are to be constructed for each land cover classes where the ecosystem services originate. Those sub-indices are finally aggregated to arrive at a final index to represent the whole political or policy boundary (Fig. 1).

Table 1
A SWOT analysis of the proposed ESC.

Strengths	Weaknesses	Opportunities	Threats
A wide range of environmental indicators are available which could be used within ES framework	The underlying relationship between ecosystem structure-processes-services is poorly understood	Develop composite for various ecosystems as well as for various spatial scales	Political misuse through inputs manipulation to support desired policy
Reduces data dimensionality and facilitate communication between science and policy	There is an inherent weakness in construction of a composite (e.g. subjectivity in weighting)	Apply in local, regional and national policy decisions	Can be challenged by users for subjectivity
	Indicators can over-simplify the complex interactions in the system	Integration of different models (e.g. i-Tree) for indicator development	

Table 2
A list of indicators needed for construction of ESC.

Ecosystem services	Indicator types	
	Direct indicators (Level-2)	Proxy indicators (Level-1)
Air quality	SO_X, NO_X concentration in the air Number of people exposed	Area of mitigation source (e.g. forest) Street density Vehicle loads
Biodiversity conservation	Plant diversity Bird diversity Diversity of endangered/rare plants and animals Proportion of native and invasive species	Area of habitats Threats density (e.g. roads, infrastructure) Fragmentation Connectivity measures Protection status
Climate regulation	Carbon sequestration rates Air temperature	Land use classes Carbon sequestration capacity
Storm protection	Historical storm data Damage data	Area of tree cover Vegetation density

4. Construction of the composite

There are five major steps involved in construction of the composite. We briefly discuss them below, but more details can be found in the cited literature.

4.1. Scoping

The structure of the ESC depends largely on the study objectives, its geographical focus as well as on the ES of interest. Therefore, the initial steps involve delineating the study or policy area,

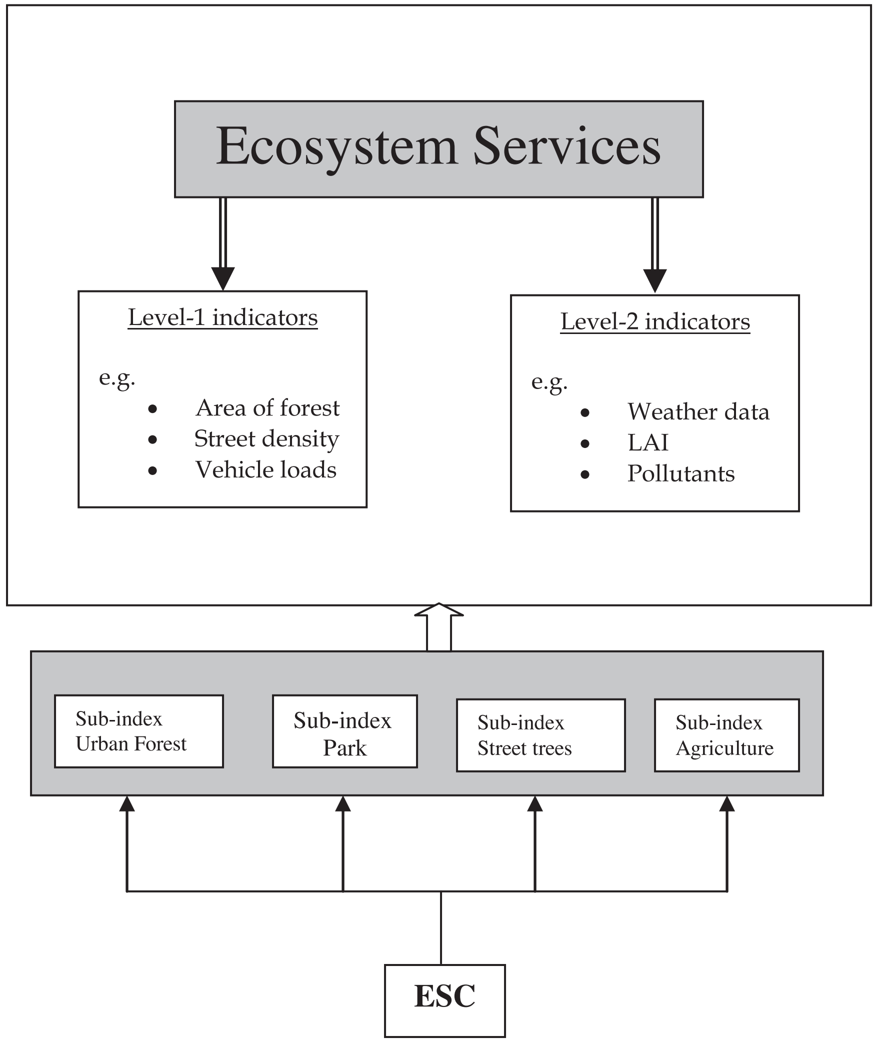

Fig. 1. An illustration of the general structure of the composite in relation to sub-indices and indicators in urban context.

mapping landscape composition and configuration and identify the ES which are relevant and important. The next decision concerns the level of analyses to be performed given the resource constraint. The number of sub-indices also has to be determined at this stage. The sub-indices could either be LULC-based or ES-based or a combination of both.

4.2. Indicator selection

Indicators are the variables which describe ES and are quantifiable. A composite indicator is the sum of its parts (i.e. individual indicators), therefore, the strength of a composite largely depends on the quality and relevance of those indicators. Although high quality variables do not automatically ensure a high quality composite, low quality variables certainly contribute to a poor outcome. Ideally, a variable should be relevant and quantifiable with readily available data of high quality.

4.3. Normalization

The ultimate aim of a composite indicator is to aggregate multi-dimensional variables into a one-dimensional metric. Normalization is an essential step in this direction where variables (which come with their own units) are put on a common scale for further treatment. Commonly used techniques are the *Z*-score, ranking, minimum-maximum approach, distance from reference and categorical scaling (Juwana et al., 2012; Koschke et al., 2012). While these techniques are commonly used in comparing country performances, we found them of limited use in the ESC since the goal here is not to rank various locations. We therefore used ‘proximity-to thresholds’ approach in which minimum and maximum thresholds are pre-defined for each variable and are based on the expected policy targets either set by international agreements (e.g. CBD) or based on expert evaluation (see next section). To avoid impact of outliers, 5% values from both ends were excluded in further analysis (Fig. 2).

4.4. Weighting

Weighting of variables is an important requirement since each indicator is expected to describe the state of ecosystem services differently and therefore have different impacts in the final composite. Weighting can follow a statistical approach (e.g. factor analysis, principal component analysis), a participatory approach (i.e. stakeholder- and expert-driven techniques) or an approach that assigns equal weights on each of them (Blanc et al., 2008; Nardo et al., 2005).

Although participatory approaches are equally relevant, we followed a heuristically developed way to weigh them on a 5-point Likert-type scale (1 being least relevant, 5 being most relevant), the reason being to reduce dependency on external resources in a level-1 composite construction. In the cases where two variables

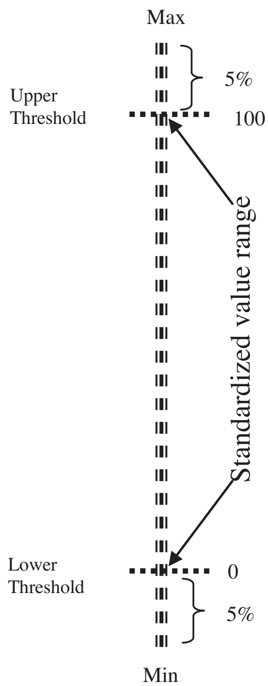

Fig. 2. Defining threshold values during normalization of indicators.

are believed to be correlated, one of them is given lesser weight than the other. Variables normalized in the previous step are then multiplied by weighting coefficients to get the 'weighted score' before they undergo aggregation in the final step.

4.5. Aggregation

The aggregation of normalized and weighted variables can be done using several rules, such as linear aggregation, geometric aggregation and multi-criteria approach. In linear functions (additive/multiplicative) every variable adds up in the composite. But there are variables which can affect the composite inversely, i.e. increase in the value of the variable decreases the ESC (such as number of vehicles in air quality composite), in which case linear functions may produce misleading results.

5. Road test: a case study of a Canadian city

The City of Mascouche, located about 60 km north-east of Montreal in Canada is the case study area (Fig. 3). The city extends over an area of 106 square kilometres and is inhabited by a population of about 45,000. Most of the land within the city boundary is zoned as agriculture, although the number of active farmers is very small. The city is situated within the temperate deciduous forest biome with an average annual temperature of 5.8 °C and average annual precipitation of 986 mm. The forest is rich in fauna and flora and is composed of a mixture of deciduous tree species with some conifers.

Table 3
Ecosystem services and indicators for the case study.

Ecosystem services	Level-1 indicators
Air quality	Area of forest High traffic street within 1 km radius Low traffic street within 1 km radius Traffic loads
Habitat	Area of forest Threat density within 1 km (area in ha) Fragmentation (length in km) Protection status (yes = 1, no = 0.75) Isolation/connectivity (yes = 1; no = 0.5)
Odour mitigation	Area of forest Area of odour source Distance from forest

In this case study we demonstrate the prototype using three services: air quality regulation, habitat provision and odour mitigation (Table 3). These were found to be highly desired services in the city. For indicator selection we performed a comprehensive literature survey of environmental and socio-economic variables impacting each ecosystem service. We then screened variables and short-listed those which met the following criteria (Layke et al., 2012; Juwana et al., 2012): (1) relevance to study context, (2) measurable, (3) able to convey information, (4) sensitive to change, and (5) availability of data. Table 3 provides a list of ecosystem services and relevant indicators for a level-1 composite. Below we describe the measurements of a few important indicators.

To measure street density around forests, the forest patches were delineated from a 2010 land cover map. A buffer of 500 m was then created for each patch. A raster layer of provincial and city streets was overlaid to calculate length of streets inside each forest patch (Fig. S1 in supplementary online material). Traffic data were collected from the Ministry of Transport of the Province of Quebec (MTQ, 2012) and the City of Mascouche (Ville de Mascouche, 2007).

To measure connectivity a buffer of 50 m was created around each patch. The patches with overlapping buffers are assumed to be connected. Connectivity was then calculated using the formula $1/A\ (A_1{}^2 + A_2{}^2 \ldots A_n{}^2)$ where A = total forest area, n = number of patches, $A_1 \ldots A_n$ area under different patches (Chan et al., 2014). As is shown in the hypothetical example in Fig. 4, patch X is fragmented, while Y and Z are connected. The measure of connectivity

Table 4
A prototype of ESC calculation for ecosystem services in urban forests.

Ecosystem services	Indicators	Raw data	Reference values	Standardized score (S)	Weight (w)	Weighted scores (Sxw)	Sub-index	ESC
Air quality	Forest area	3153 ha	472 ha	5	0.6	3		
	Street length	335 km	10 km/100 km^2	5	0.1	0.5	1.9	
	Traffic load	4000 day^{-1}	1k–10k day^{-1}	2	0.3	0.6		
Habitat	Forest area	3153	15% of city area	5	0.8	4		
	Threat density	335 km	10 km/100 km^2	5	0.05	0.25	3.56	39.1
	Fragmentation	31.2 km	0 km ha^{-1}	5	0.07	0.35		
	Connectivity	868.9 ha	782 ha	2	0.08	0.16		
Odour mitigation	Source 1	1.5 ha	0–5 ha	1	0.3	0.3		
	Buffer 1	10 ha	1–50 ha	5	0.2	1	0.4	
	Source 2	3 ha	0–5 ha	3	0.3	0.9		
	Buffer 2	2.5 ha	1–50 ha	3	0.2	0.6		

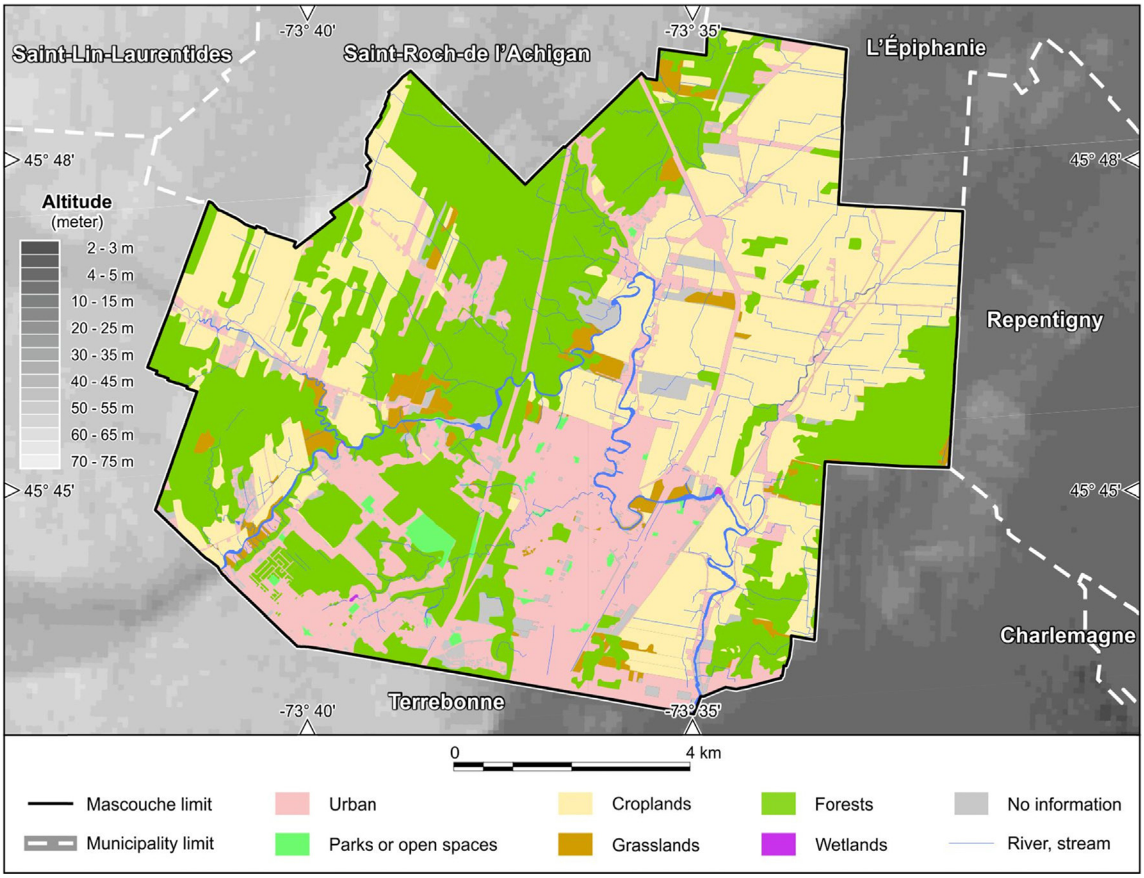

Fig. 3. Land cover map of the city of Mascouche showing dominant land cover types.

therefore would be = 1/32 $[14^2 + (10 + 8)^2] = 16.24$. As for the fragmentation data, GIS layers of forest patches and city streets were overlaid and then the total length of the streets within the forest patches was calculated.

Horse shelters were found to be a major source of odour in the city of Mascouche. The odour area was determined by a 500 m buffer around the point of odour sources. The distance between the odour source and nearest forests was then averaged.

After measuring the variables raw scores were converted to a scale of 0–1, based on distance from the reference values. They were then weighted heuristically. Following normalization and weighting, a two-step process was employed for aggregation of scores. Step one involves synthesis of variables within each sub-index using equations depending on correlation and interaction among variables. The second step involves aggregation of the sub-indices into a final composite through an arithmetic mean. Table 4 provides a prototype of the ESC along with raw data and reference values. The reference values were derived based on expectations (e.g. 15% of urban areas under tree-cover), recommendations (e.g. traffic load recommended by authorities) and assumptions (e.g. average odour

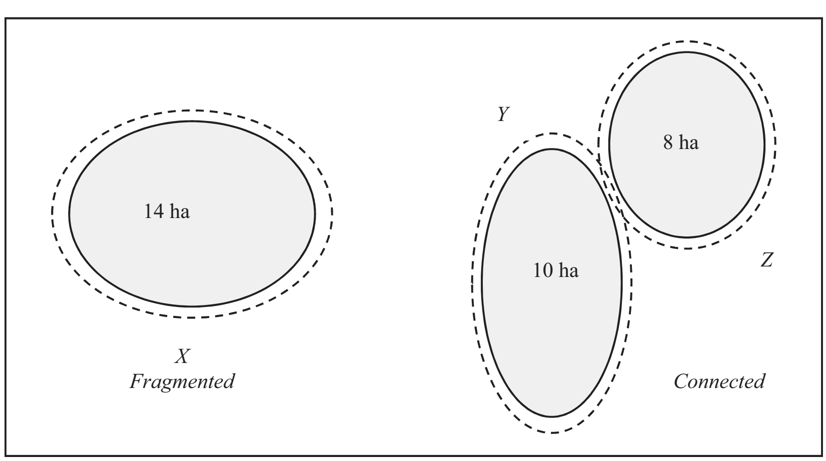

Fig. 4. Measuring connectivity, a hypothetical example.

source to be an area 0 to 5 ha). Score sheets for other land use and land cover types such as agriculture areas, riparian buffers, street trees and urban parks are provided in Supplementary Online Materials (see Tables S2–S5).

6. Discussion and conclusions

Although composite indicators are frequently used in environmental monitoring, they are scarce in ecosystem services context (but see Liu et al., 2013; Müller and Burkhard, 2012). In this study we demonstrated how to construct a level-1 composite using indicators in an urban forestry context. Future works are underway to develop a more robust (i.e. level-2) composite using a larger set of indicators so that it is applicable in other study areas with similar ecological and urban characteristics.

Collection of primary biophysical and economic data is often resource intensive. In resource-scarce situations the composite can address research and policy questions with less effort. In contemporary literature, spatially explicit ES analyses use proxies such as land use (Crossman et al., 2013), functional traits (Lavorel et al., 2011), economic value (Costanza et al., 2014) and species-area scores (Nelson et al., 2009). The ESC scores developed based on several such proxies will enhance our understanding of spatial distribution of ES and their trade-offs in a multivariate environment. And finally, one of the obstacles in adoption of an ES framework in decision making is the use of scientific jargons, which impedes an effective communication between science and policy. The use of the ESC can overcome this challenge as it is simply a numeric value and the indicators used for developing ESC are familiar variables.

Considerable opportunities exist for improvements on the composite. First, repeated measurements of time-sensitive variables will improve the scores. For example, number of people visiting an urban park may vary greatly between seasons. Therefore, if it included as a variable the seasonal variability needs to be accounted for. Second, the use of a heuristic approach in weighting variables does not help a quantitative model validation. In lieu of such validation a sensitivity analysis can improve its robustness. Further, a number of uncertainties remain, for example, in the selection of variables, methods of dealing with missing data (if any) and weighting and aggregation methods (Nardo et al., 2005). And finally, normalization using the approach demonstrated in this paper has the limitation of being too sensitive to extreme values, which could represent unusual behaviours and therefore may have unexpected impacts in the final composite (Blanc et al., 2008).

In conclusion, this article demonstrates a new composite indicator for ecosystem services that presents a potential to integrate ES in decision-making and land-use management by aggregation of multiple ES, monitoring changes temporally and understanding trade-offs. Here we presented an example of how the composite can be developed. Future work is needed in order to integrate more ecological and socio-economic information in a more complex version of this composite indicator.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2015.05.035

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