Spatial aggregation of indicators in sustainability assessments: Descriptive and normative claims

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To cite this version:

Sandrine Allain, Gaël Plumecocq, Delphine Burger-Leenhardt. Spatial aggregation of indicators in sustainability assessments: Descriptive and normative claims. Land Use Policy, 2018, 76, pp.577-588. 10.1016/j.landusepol.2018.02.038 . hal-02621725

HAL Id: hal-02621725
https://hal.inrae.fr/hal-02621725v1

Submitted on 26 May 2020

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Spatial aggregation of indicators in sustainability assessments: descriptive and normative claims

Abstract

Indicators are widely used in sustainability assessments. They serve both a descriptive function (i.e.., assessing a situation or effects of potential changes) and a normative function (i.e., allowing the expression of value judgments). These functions are usually considered when identifying and using indicators. However, processes such as formalization, estimation, and customization are needed to produce tangible indicators. These processes and their influence on sustainability assessments are studied less often. We focus on spatial aggregation, a specific type of customization commonly used for landscape-scale and regional assessments. Using a database with 146 indicator profiles for water management, we investigated reasons for spatial aggregation choices, i.e. whether indicators based on spatially-explicit data are aggregated while under development or are provided to users in a disaggregated form. Although the literature assigns a descriptive function to spatial aggregation, our database shows that reasons underlying aggregation choices are more diverse. These reasons include highlighting differences, fitting to the scale of a process, fitting to criteria, recognizing a lack of knowledge, expressing social rationality, contextualizing information, and allowing different interpretations of the same indicator. Some of these reasons reflect the choice to expand or reduce the range of potential uses of an indicator, and therefore the potential for different viewpoints to confront each other. Hence, normative claims combine with descriptive claims when aggregating indicators, and even more so when customizing them. In general, the form of indicators merits more attention in the practice and theory of sustainability assessments.

Highlights

- Indicators are viewed as objects to describe and debate a situation.
- Indicators result from different information processes that are sometimes “hidden”.
- The process of spatial aggregation is investigated.
- Spatial aggregation choices provide a degree of leeway in interpreting indicators.
- Choices illustrate tension between the need for consistency and that for diversity.

1. Introduction

Sustainable management of natural resources requires governance that considers long-term dynamics and the spatial scale of the resource managed and that allows different actors to

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participate in the decision-making process. Sustainability assessments combine tools that can assist decision-makers in this task (Ness et al., 2007). Most sustainability assessment tools require indicators, which can be used to assess a situation and measure progress towards sustainable development (Pires et al., 2017; Singh et al., 2012; Smeets et al., 1999) or areembedded in prospective methods to assess scenarios involving change or policy options (Leenhardt et al., 2012; Singh et al., 2012).

Several guidelines and methods exist to identify relevant sets of indicators for sustainability assessments (Alkan Olsson et al., 2009; Bockstaller et al., 2009; Kurka and Blackwood, 2013; Reed et al., 2006; Valentin and Spangenberg, 2000), and the variety of methods reflects the diversity of contexts in which indicators are used. For instance, within "governance contexts"(Hezri and Dovers, 2006), in which people outside of the political elite participate in the decision-making process, indicators cannot be produced according to a clearly identified audience (Hezri and Dovers, 2006). Considering this, several authors claim that identifying indicators should be a social learning process that involves multiple participants (Bell and Morse, 2004; Fraser et al., 2006; Valentin and Spangenberg, 2000).

The large number of studies on indicator identification could suggest that defining the indicator set is the only crucial step of information processing, from which comes results of the sustainability assessment. However, other processes occur between defining the relevant indicator set and evaluating a situation or option. For spatial decision support systems, Uran and Janssen (2003) noted that "output sometimes needs simplification, aggregation, structuring, or another form of processing in order for it to be used in a decision-making process. In some systems this is done automatically, or 'hidden', so the user is unaware of the fact that an evaluation step has been made". This highlights the need to clarify and question the entire chain of processes required to develop indicators (and not only to identify them); this is the core motivation for this article.

More specifically, we focus on spatial aggregation, a specific process that occurs after an indicator is identified. Spatial aggregation entails changing fine-resolution data into coarser-resolution data (e.g., the entire landscape or region) to derive "meaningful" information. We distinguish "data" from "information" according to definitions of Pahl-Wostl et al. (2013): "'Data' are symbols, such as the numbers produced by a temperature-measuring device, whereas 'information' places data in relation to some meaning that makes them useful (e.g., impacts of July temperature on the yield of a certain crop)." Spatial aggregation is often considered to serve a descriptive purpose: spatial aggregation choices (e.g., which aggregation pathways, which spatial resolution) can depend on the characteristics of the model used (Faivre et al., 2004; Janssen et al., 2009), on the process the indicator intends to describe (Alkan Olsson et al., 2009), or on the expected assessment scale (Chopin et al., 2017). Spatial aggregation clearly differs from indicator

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aggregation, which involves condensing several indicators into a smaller number of indicators. Indicator aggregation is known to embed normative values and thus go beyond describing social-ecological processes (Böhringer and Jochem, 2007; Mayer, 2008). For instance, ecological economists have demonstrated that using compensatory or non-compensatory rules to aggregate indicators respectively entails a weak or strong conception of sustainability (Garmendia and Gamboa, 2012; Martinez-Alier et al., 1998). However, since ecological economics is as unfamiliar with spatial decision problems (Allain et al., 2017) as spatial planning is with non-equivalent descriptions of a problem (Ramsey, 2009), spatial aggregation of indicators is not studied as a normative process.

We consider spatial aggregation both a descriptive process (i.e., translation of information in a formal system) and a normative process (i.e., in which actors express value judgments). To explore how descriptive and normative aspects are combined when considering a sustainability issue with a spatial dimension, we used a database of indicator profiles built to compare water management options.

2. Definitions and theory

2.1 Defining "indicator"

The term "indicator" has multiple definitions (Abbot and Guijt, 1998), and most authors use a finalist or functionalist definition, in which indicators are defined according to their purpose. Consequently, the nature of indicators remains ambiguous: i.e., whether indicators are ideas, variables, objects, variable values, etc.

In quantitative assessments, an indicator set is generally displayed in a table containing the names of variables and some additional attributes, such as definitions, scales, calculation methods, and units. In this sense, indicators are variables, and a situation is assessed according to their values (Chopin et al., 2017). However, from a deliberative perspective, "indicators" include outputs of analysis ("The species is not impacted by gear, as a secondary involuntary catch, in any significant way"), variables ("Gross efficiency of the catch (catch/net P.P.)") or ideas for analyses ("Length/Frequency analysis of catches") (examples from Douguet et al., 2010). In addition, Meadows (1998) stated that "Indicators can take many forms. They don't have to be numbers. They can be signs, symbols, pictures, colors." Consequently, when indicators are identified in contexts with multiple actors, the term "indicator" represents any type of argument, be it a suggested analysis, a quantitative result, a color or a photograph, that empowers someone to assess or judge a situation.

Although the vagueness of the term "indicator" may be useful in deliberative contexts, for the purpose of this article, we consider a narrower definition: *an object with meaningful qualitative or*

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quantitative information that facilitates learning about a situation and forming a value judgment about it. This definition assumes the existence of one or many indicator developers, i.e. those who, from a heterogeneous set of suggestions (of varying degrees of development) for potential indicators, create a set of formal objects (the indicators).

2.2 Steps in indicator development

Our analysis focuses on indicator development, a stepwise process of coding information that occurs between the processes of identifying potential indicators and using them (Fig. 1). We provide insights into indicator identification and use before describing intermediate processes involved in indicator development.

The literature on indicator identification highlights qualities that a “good” sustainability indicator should have (Reed et al., 2006), which are generally linked to the latter’s soundness and ease of use. The literature also contains many frameworks developed to derive indicator sets, such as goal-oriented frameworks (Alkan Olsson et al., 2009), multi-scale and systemic frameworks (Astier et al., 2012; Bossel, 1996), and ecosystem-service frameworks (de Groot et al., 2010). Methods to identify indicators are as varied as the frameworks. They can be divided between top-down (a generic framework transposed or adapted to a local context, e.g. Speelman et al. (2007)) and bottom-up approaches (indicator sets are derived from locally relevant issues, and generic knowledge is used to explore these issues, e.g. Fraser et al. (2006)). Both can involve experts and stakeholders, and can be implemented in a deliberative approach involving “extended peer communities” (Funtowicz and Ravetz, 1990) or in a prescriptive approach. Within deliberative approaches, developing an indicator “profile” (i.e., meta-information related to the scientific validity of an indicator and its relevance to the context in which it will be used) is considered a crucial element of knowledge quality (O’Connor and Spangenberg, 2008; Sluijs et al., 2008).

Management science studies of the performativity of indicators and their use as management tools in organizations and society (Desrosières, 1997; Espeland and Sauder, 2016) have inspired a literature on the uses of sustainability indicators. Some authors clearly distinguish indicator uses from misuses (Lyytimäki et al., 2013), suggesting that safeguards are required to avoid inappropriate uses. Other authors build on the principle that the users and uses of sustainability indicators are diverse. For instance, Hezri and Dovers (2006) distinguish five types of indicator uses for policy-making in a governance context: instrumental (to solve problems), conceptual (to increase understanding), tactical (as a “substitute for action”), symbolic (as “ritualistic insurance”) and political (to support a pre-defined position). Because we focus on using indicators for group deliberation rather than effective policy-making, we consider it more appropriate to distinguish a descriptive function from a normative function of indicators (see section 2.3).

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Indicator development proceeds stepwise, with the potential for several iterations and feedback between steps (Fig. 1). After indicator identification (step 1), "formalization" (step 2) is necessary to help select variables and specify characteristics of future indicators. Indicator profiles result from this formalization, and they may be transferred to similar issues or serve as a source of inspiration for different issues. Next, "estimation" (step 3) produces raw data (e.g., values of the variables selected for the case study that are obtained through expertise, simulation or a data search). "Customization" (step 4) includes all activities that provide meaning and tractability to outputs of the estimation (Leenhardt et al., 2012), such as spatial aggregation, classification (aggregating into classes), creation of archetypes, and shaping (e.g., into a map, a graph). The result of customization is called an "indicator" (see section 2.1). The last step, indicator use (step 5), follows development of indicators. It has another nature: it produces knowledge, defined as information embedded in a context of interpretation (Pahl-Wostl et al., 2013). As emphasized by O'Connor and Spangenberg (2008), knowledge *based on indicators* and knowledge *about indicators* can be derived from indicator use. This knowledge about indicators feeds back into the previous steps of indicator development and can help to identify and develop new indicators and discard or modify other indicators.

2.3 Assessment and evaluation

Indicator use can refer to "assessment" or "evaluation" (Fig. 1). Although they are generally used synonymously, we use the terms to indicate two different activities. Assessment is a descriptive activity in which a user an indicator is compared to other estimated values or references. For instance, the workload on different farms may be measured or estimated, which provides a basis for *assessing* which farms have a workload that *surpasses* the national average. Evaluation is the process of assigning a value judgment to the information, such as whether the workload is *acceptable* or *fair*. In short, one *assesses* when stating that the workload is "high" but *evaluates* when claiming that it is "too high". In contexts with multiple stakeholders, assessment allows for confrontation of different descriptions of a situation, while evaluation allows for confrontation of different value systems.

Because confrontations are essential to democratize knowledge-production and decision-making processes (Funtowicz and Ravetz, 1993), we consider that a "good" indicator should be useful both for assessing and evaluating a situation or alternative option. Deliberative sustainability assessment (Frame and O'Connor, 2011) and systemic sustainability analysis (Bell and Morse, 2004) are frameworks for identifying indicator sets that explicitly recognize this duality. However, these frameworks do not mention that the duality of indicators influences both indicator identification and all of the steps that transform indicators into usable forms (Fig. 1). More specifically, because

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customization generates meaning, it influences indicator use and in return is influenced by the expected uses. Using the specific case of spatial aggregation, our analysis illustrates how normative considerations become relevant in the customization process.

2.4 Spatial aggregation

In defining spatial aggregation as the conversion of fine-resolution data into coarser-resolution data (e.g., the entire landscape or region) to derive “meaningful” information, we emphasize changes in scale and in meaning. Different methods can be used to aggregate spatial data (Chopin et al., 2017; Ewert et al., 2011), but discussing them in detail lies outside the scope of this article. Sustainability assessments at regional or landscape scales usually include spatial aggregation, since indicator developers tend to have wide access to spatially-explicit data at these scales. Consequently, the issue of spatial heterogeneity arises (i.e., should they use average values, quantify heterogeneity, or keep the data at the finest resolution?).

Systematic aggregation of spatial values into a single value is criticized as an oversimplification of the processes targeted (Scholes et al., 2013) or because of its opacity to decision-makers (Janssen et al., 2005; Uran and Janssen, 2003). Nevertheless, maintaining spatially disaggregated values, generally by displaying them on maps, is costly and introduces a high level of cognitive complexity that can be difficult for users to handle (Jankowski et al., 2001). Similarly, Uran and Janssen (2003) suggested that providing disaggregated data is useful when users have sufficient skill in processing spatial data or when they are guided in their interpretation.

However, while we recognize diverse uses and multiple users of indicators, it seems difficult to target the use of (at least some) indicators to a few specific users. Therefore, to enrich the debate over spatial aggregation, we assume that descriptive and normative uses cannot be separated and that users cannot be defined beforehand.

3. Materials and Methods

Here we present (i) how we built the database of indicator profiles on which we based our spatial aggregation analysis, (ii) the database itself, and (iii) the objective and method of the analysis.

3.1 Origin of the database of indicator profiles

The database of indicator profiles was developed by implementing steps 1 and 2 described above (Fig. 1) to address water management in the downstream area of the Aveyron watershed (southern France). This agricultural area experiences a structural water imbalance in the low-flow period, when low rainfall coincides with maximum water needs for agriculture. Water management is based on water restrictions that are implemented when river flow falls below a specific threshold. Since

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national and European policies advocate for more structural management options (Erdlenbruch et al., 2013), we created a set of potential indicators to assess contrasting water management options and encourage public debate over future water management in the Aveyron watershed. Because the topic of agricultural water management is complex and prone to conflict in the area, undertaking the sustainability assessment of different scenarios challenges both our ability to represent the social-ecological processes at stake and create the conditions for dialogue between stakeholders.

This context drove our choices for developing indicators. Social mistrust and power asymmetries made collective meetings impossible from the outset and a top-down approach risky. Therefore, we opted for a bottom-up approach, based on card-sorting interviews with local and regional stakeholders (Allain et al., 2016), to construct a grid of criteria (Table 1) reflecting the plurality of stakeholder preoccupations. Then, we used these criteria to identify (step 1) and formalize (step 2) the indicator profiles.

Although stakeholders sometimes suggested useful indicators or “proto-indicators” (ideas for indicators, with a variable number of guidelines for their scale, representation, calculation, etc.), most indicators were identified through a series of 14 meetings with scientific or technical experts, most of whom worked in the region. We asked the experts to suggest potential indicators that corresponded to the criteria defined by stakeholders, were relevant at the landscape scale, and if possible, could be estimated quantitatively or qualitatively using model simulations, expertise, or by processing geographic information. Expert interviews included questions to facilitate formalization, such as at which spatial and temporal scales the indicator would be relevant.

Stakeholder and expert interviews led to identification of 156 proto-indicators. We specified complete profiles for 146 of them based on our own expertise. The remaining 10 reflected arguments stakeholders provided that neither we nor the experts we met with could transform into variables assessable in an *ex ante* manner.

Although the same individuals were sometimes interviewed twice, first as a stakeholder to identify criteria and then as a local expert to suggest indicators, we could not push the ideal of democratizing indicator development further. One reason was that local stakeholders, such as reservoir managers or farmers, use many indicators in their everyday life (e.g. the plant-growth stage for farmers to launch irrigation, the level of water in reservoirs for public agents to release water into rivers). Switching from the time and space scale of operational decisions to the scales of the landscape and multiple years is challenging to them. Also, we aimed at assessing scenarios and not real situations. We therefore had to identify and develop indicators not measurable here and now, hence disconnected from what practitioners are accustomed to handle. These barriers can be levered, but the time required to do so was prohibiting (to stakeholders and to us researchers).

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Hence, for our case study, we, the experts we interviewed, and colleagues who helped specify and interpret indicator profiles served as indicator developers.

3.2 Database of indicator profiles

The database (see Appendix) contains 146 indicator profiles (123 based on spatially-explicit data), with details on the following attributes:

- Indicator definition
- Meaning: related criteria, justification for suggesting the indicator
- Estimation: estimation method (model simulation, expertise, calculation based on scenario characteristics), scale of raw data (e.g., field, farm, elementary watershed, river, entire landscape)
- Customization: type of representation preferred (e.g., simple value, graph, map, illustration, narrative), aggregation scale
- Evaluation scale: landscape or landscape + sub-landscape

3.2 Analysis of spatial aggregation

We analyzed the indicator profiles in the database with no additional input from stakeholders or experts. We focused on the attributes of 115 “horizontally” aggregated indicators (i.e., those that are based on spatially-explicit raw data provided for multiple locations and thus require aggregation during either indicator customization or use to become relevant at the landscape scale). Indicators referring to only a point location (e.g., a watershed outlet) were not considered horizontally aggregated because a single value at a single point cannot reflect any spatial heterogeneity. Horizontal aggregation differs from “vertical” aggregation, which yields composite indicators or overall sustainability scores (Allain et al., 2017).

We analyzed the 115 profiles according to who performs the spatial aggregation: developers (during customization) or users (during use). For the former, developers aggregate raw data to obtain a coarser resolution (partial aggregation) or a landscape-scale indicator (complete aggregation) (Fig. 2). Under partial aggregation, outputs remain heterogeneous. Partial aggregation can remain spatially explicit (e.g., zones) or yield non-spatial classifications (e.g., farm types). Complete aggregation results in a single value for the entire landscape. In user-led aggregation, users aggregate spatially heterogeneous information to assess or evaluate the entire landscape. User-led aggregations are therefore necessarily complete, although some indicators can be used to assess or evaluate landscape zones or classes in addition to the entire landscape.

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We reflexively clarified reasons underlying developer-led and user-led aggregations, since we were involved in the identification and formalization processes for all indicators, most of the time as indicator developer interviewers but also as developers (see 3.1). Our aggregation choices were not discussed with the stakeholders expected to use them because the research was not part of a joint project in which stakeholders are clearly named. Also, as our experience showed, people get involved and interested at one moment and then, as the research progresses, other people participate in it. This prompted us to consider a wide range of potential users and favor, when possible, indicators prone to diverse interpretations.

4. Results

In presenting results for the 115 indicators, we use 15 indicators as examples to illustrate important points[1] (Table 2).

4.1 Reasons underlying developer-led spatial aggregation

4.1.1 Partial spatial aggregation

The database of indicator profiles shows that only six indicators, associated with four criteria (“safety”, “biodiversity”, “adjustment potential”, and “maintaining natural capital”), should result from partial spatial aggregation. For each, raw data estimated at the field or field-islet scale should be aggregated according to the landscape’s hydrological zones (elementary watersheds) or water management zones (e.g., for water restrictions). Reasons underlying partial aggregation were similar to those for aggregation into classes, which indicator developers chose for 24 indicators (for the criteria “local identity”, “wealth and employment”, “long-term adaptability”, “adjustment potential”, and “equity” and “efficiency“). For these indicators, raw data at the field or field-islet scale should be aggregated by crop or farm type.

We identified three main reasons for partial aggregation:

- *to highlight differences* (between zones or classes). For instance, the indicator “area affected by water restrictions at key periods” estimated at the field scale should be aggregated at the

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[1] We often refer to characteristics of “indicators”, but the characteristics are those of profiles and not of the indicators themselves. Indicator profiles (mainly “definition”, “scale of raw data”, “aggregation scale”, “representation”, and “estimation method”) provide guidelines for spatial aggregation that will be usually strictly implemented to produce the indicators, because many calculations are based on long simulations. This constraint, which precludes a trial-and error approach, also explains the time and effort devoted to clarifying aggregation choices. In certain cases, an indicator profile allows for multiple aggregation scales, which can generate several indicators (one per scale). Consequently, although reasons underlying aggregation choices can be analyzed before indicators are produced, quantitative data (the number of indicators concerned) should be considered only indicative.

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scale of water restriction zones. This would allow users to visualize whether certain zones are more affected than others, and in which zones farmers have less leeway to adjust crop management practices during the year. Likewise, raw data for "irrigation costs per ha" should be aggregated at the crop-type scale to compare crop types and thus provide an indication of how fairly costs are shared.

- *to make an indicator more relevant for the targeted criteria*. For instance, the indicator "variation in water stored in soils" estimated at the field scale could be used "as is" to describe the resilience of farms or crops to water stress; however, to produce an indicator informing the "maintaining natural capital" criterion, data should be aggregated at the elementary watershed scale.
- *to fit the scale of a process*. For instance, since the indicator "pollution from plant protection practices" describes water pollution caused by agricultural chemicals, raw data should be aggregated at the elementary watershed scale. Aggregation scales could vary to reflect other processes, such as pollution of food products or soils. This reason appears linked to the use of pressure indicators, which are often needed in *ex ante* assessments since direct measurements and model simulations are not always possible.

Our study yielded one reason specific to aggregation into classes: to *increase the intelligibility* of indicators. Because the study area has many fields and farms, data at these two scales become unintelligible when considering the entire landscape. Classifying thus renders fine-resolution data tractable.

4.1.2 Complete spatial aggregation

The database of indicator profiles contains 79 indicators (among the 11 criteria) that should be completely spatially aggregated. Two reasons identified for partial aggregation also exist for complete aggregation: relevance for the targeted criteria and fit to the process scale. The former is illustrated by the indicator "volume of rainwater returned to the environment", which qualifies the biophysical system (the water system, in the "maintaining natural capital" criterion). Since it does not seek to indicate the extent to which each water user manages water capital, it should be aggregated at the landscape scale. The second reason (fit to the process scale) is illustrated by the indicator "irrigation capacity of all farms". Although its raw data, at the farm scale, can be meaningful at this scale, the experts who suggested this indicator referred to the potential to expand irrigation to additional fields and reallocate water within and among farms. It was also meant to address how quickly agriculture can respond to shocks (e.g., a rise in maize price), which justifies aggregation at the landscape scale.

We identified three additional reasons for complete aggregation:

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- *easily comparing management options* by providing a single value. For instance, the indicator “impact of water use restrictions on agricultural yields” (“adjustment capacity” criterion) should be aggregated at the landscape scale for two reasons: (1) information would be too complex at smaller scales (e.g., field or farm) and (2) aggregation by farm type or crop type would mask a potential imbalance among the number of each type. Thus, each field’s production should be aggregated to calculate a landscape-scale value. To make this choice, developers assumed a commensuration process, i.e. to consider all crops and all farms equivalent.
- *addressing uncertainties*. An example related to model and data uncertainties is the indicator “use rate of reservoirs”, based on model predictions. Since data for individual water withdrawals were unavailable, accuracy of the model (MAELIA, Gaudou et al., 2013) could be verified only by comparing its predictions with observed data for river flows and cumulative water withdrawals. Also, allocating a withdrawal point to a field was based on simplified decision rules that are uncertain at the field scale but robust at the landscape scale. Consequently, the indicator could be used only to quantify cumulative use of reservoirs and not use of each reservoir separately. Other uncertainties arise from a lack of knowledge. The indicator “semi-natural elements contributing to water purification” is a good example. It was aggregated at the landscape scale because we simply do not know enough about water purification processes. It is incorrect to assume that the degree of water purification increases linearly as the area of forest or grassland increases. Thus, aggregating this indicator at the landscape scale seems a more accurate approach than not doing so.
- *prompting expression of social rationality*. The indicator “match between water storage capacity and irrigation needs” (“efficiency” criterion) seeks to reflect how farmers collectively manage the available infrastructure. At a disaggregated scale, it would indicate whether individual farmers use their reservoirs efficiently or not. This is why complete aggregation was preferred.

4.2 Reasons underlying user-led aggregation

The 115 horizontally aggregated indicators can be split in two groups after customization:

- 71 indicators that already exist at the scale of the evaluation and therefore do not require users to aggregate. Most are at the landscape scale (to assess/evaluate the landscape), but some are also at smaller scales and can be used to evaluate/assess both the landscape and sub-landscapes.

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- 44 indicators require users to aggregate. Indicators in this group are at sub-landscape scales (sometimes also at the landscape scale) but are meant to be used to assess/evaluate only the entire landscape.

Several reasons explain why these 44 indicators should not be completely aggregated during customization and why users must perform at least some of the aggregation:

- *Visualizing variability or distribution patterns*, allowing users to interpret it/them. This applies mainly to indicators related to the "equity" criterion, such as the indicator "farms concerned with increase/decrease in water costs". This variability can be expressed spatially (e.g., in maps) but also statistically (e.g., in boxplots) to help users interpret it.
- *Promoting expression of diverse (and possibly conflicting) interpretations*. Indicator developers can choose to let users perform the commensurations that the latter judge relevant or to use only some of the information produced. For instance, the indicator "two-year flood flow" ("safety" criterion) should be provided for the outlet of each sub-watershed. Users can consider the indicator value at the most downstream outlet in the watershed to compare water management options "in general" for the entire watershed, or consider the value for the river where they consider safety concerns greater.
- *Contextualizing information* provided by the indicator. For instance, the indicator "impacts on the number of recreational water activities" should be provided for each site of activity, even though this diversity could be expressed more simply by the number of potential activities. Presenting the indicator in a spatially-explicit way supports users' learning capacities (i.e., they can understand better the source of its values) and expression of expertise (i.e., they can appreciate a value better when they know what it refers to). This reason often accompanies the previous reason of diverse interpretations.
- *Acknowledging a lack of knowledge*. In this case, the indicator is provided in a spatially disaggregated form, which makes interpretation difficult, nay, impossible, but developers still convey to users that, despite being weak for landscape-scale assessments, the indicator matters. A change in its value reflects a change for a specific location or context, but not enough knowledge is present to infer impact at the landscape scale. For instance, the indicator "nitrate pressure" should be provided at the elementary watershed scale but not for the entire landscape. Nutrient flows are complex processes, which makes it difficult to convert pressure on water quality into a quantified impact. Another example, the indicator "changes in gross margin generated by each type of agricultural production", considered a proxy for employment and wealth, should be provided for each type of production. This indicator lacked complete spatial aggregation because the influence of gross margin on employment and wealth remains little understood.

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5. Discussion

5.1 Many reasons underlie aggregation choices

Our analysis empirically illustrates how descriptive and normative claims together influence indicator development and more specifically aggregation choices. We showed that customization, which modifies the information provided by an indicator and its potential uses, is shaped by developers' subjectivities. For instance, by providing users with an indicator in a spatially disaggregated form, developers can decide to widen interpretations of the indicator or can complicate indicator use by making it difficult to interpret. Similarly, by aggregating, developers can limit potential uses of an indicator, for instance by prompting the expression of one type of rationality only, e.g. social rationality over individual interests.

Although researchers who study customization of spatial indicators and spatial aggregation problems acknowledge that these processes are non-neutral and affect indicator uses (Janssen et al., 2005; Malczewski and Rinner, 2015; Uran and Janssen, 2003; Walz, 2000), they generally justify or question customization choices in terms of "functionality" (Uran and Janssen, 2003). Accordingly, customization choices result from a trade-off between ease of use and "scientific soundness". These choices could be optimized according to customization rules (e.g., a maximum number of colors, a spatial resolution that allows patterns to be perceived quickly).

Among the reasons for spatial aggregation highlighted in our analysis, most of them can be understood in terms of functionality. These reasons include relevance for the criteria, fit to process scale, addressing uncertainty, increased intelligibility, contextualization, increasing the visibility of variability and easily comparing management options. However, the desire to make an indicator more functional does not always completely underlie them. Developers can also intend for users to focus on differences within the landscape by highlighting its heterogeneity or on differences among management options by providing a single quantitative value for each option. Furthermore, other reasons escape the logic of functionality (i.e. increasing indicator's ease of use and ability to describe univocally and accurately a management option for a given criterion), such as promoting expression of diverse interpretations or prompting social rationality. The former reflects a desire to yield multiple indicator uses rather than the only "right" use. The latter reason shows a desire to promote specific indicator uses agreeing with developers' view of the problem.

As a result, when indicators are expected to foster deliberation among multiple actors, spatial aggregation cannot be viewed only through the lens of functionality. Functionality primarily makes an indicator accessible to those with different skills in a way that is consistent with the system/problem described. It therefore agrees with a descriptive view of indicators as tools to measure progress towards sustainability. However, when confrontation of value systems is

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considered another role of indicators (Bell and Morse, 2004; Frame and O'Connor, 2011), customization can influence the degree of leeway available for interpreting indicators. Consequently, customization is one way to increase and/or decrease the number of potential value judgments.

5.2 What should drive aggregation choices

By making customization choices, indicator developers influence the size of the "interpretation space" left to users. Developers tend to decrease the space for what they consider indicator "misuses" and to increase the space for what they consider "legitimate uses" (but they can also consider that providing a large amount of space is intrinsically good). The issue then arises of whether certain aggregation choices are more legitimate than others. In other words, what should guide aggregation choices besides functionality? We provide two responses that are related to the collective nature of the problem and the commensuration issue inherent in all information aggregation processes.

Environmental appraisal methods can be considered value-articulating institutions (as defined by Vatn (2009)) because they address problems that are collective in nature and that promote expression of different types of rationality. For instance, for managing common goods, methods that promote expression of social rationality rather than the confrontation of individual interests should prevail (e.g., the forum rather than the market) (Vatn, 2009). Fine-resolution, spatially-explicit indicators can encourage expression of individual interests in certain cases since they can, for instance, allow users to consider impacts on an individual's private property. Customization can be a useful way to switch from individual to social rationality. For instance, partial aggregation could blur individual information or show values in a boxplot to transform spatially-explicit heterogeneity into statistical heterogeneity.

However, aggregation, whether spatial or not, implies commensuration, i.e. comparing different objects according to a single measurement unit (Espeland and Stevens, 1998; Martinez-Alier et al., 1998). In spatial aggregation, spatial entities with different values for an indicator are summed or averaged into a single value for the entire area considered. We posit that indicator developers should first address the commensuration issue by considering the extent to which different spatial units are commensurable. It may not be appropriate to make performances of farms on alluvial plains commensurate with those of farms in the hills. Some may advocate that performances can be calculated relative to a location-based potential and that it is acceptable to provide an aggregated value. In contexts with multiple actors, however, the relevance of spatial aggregation as a commensuration process should be framed in normative terms (i.e., whether aggregation helps or hinders confrontation of value judgments). If we consider indicators as "channels for bridging

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realities and meanings" (Abbot and Guijt, 1998), this indicator would probably be more relevant in a spatially disaggregated form, even though it would make comparisons among management options more complex.

Other experiences with the uses of maps (which are by essence spatially-disaggregated representations) in governance contexts support our argument that the commensurability of viewpoints should drive spatial aggregation choices. The use of maps as deliberation support tools (Caron and Cheylan, 2005; Lardon and Piveteau, 2005; Rinner, 2006) show that they can mediate the expression and confrontation of different viewpoints. Similarly, the emergence of participatory or collaborative mapping (Goosen et al., 2007; Jankowski, 2009) strengthens the claim that spatialization is a powerful tool for empowering people, even those who are marginalized. Finally, studies in the field of landscape aesthetics have shown that although landscape metrics are correlated with visual preferences of the landscape, stakeholder groups do not value the same aspects of the landscape (Dramstad et al., 2006; Howley, 2011), which argues in favor of using landscape visualizations when users are not known beforehand. These studies reinforce the idea that spatial representations and other disaggregated forms can help make evaluations more deliberative, under certain conditions. This claim differs greatly from the use of horizontally and vertically aggregated forms (i.e., numbers) in most decision-making tools, including sustainability assessments.

When considering the normative role of indicators, aggregation choices can increase the ability of users to interpret indicators according to their values and knowledge while moving beyond individual interests. More generally, although identifying indicator sets is a necessary information compression (Giampietro et al., 2006), indicator customization can help to reintroduce plurality and social rationality into the debate. Finally, there is no contradiction between the normative role and descriptive role of indicators, but there is a tension between the need for consistency (e.g., in the final assessment/evaluation scale(s), in the "common" nature of the problem) and the need to represent diversity (e.g., spatial heterogeneity, plurality of individual values).

Therefore, when developing indicators, we recommend developers to investigate the following questions:

1. What are the scales that are consistent with the processes at stake, the assessment criteria, the level of commensurability between the different spatial units, the nature of the problem tackled and the model used? Answering this "consistency" question bounds the possibilities for aggregation choices. If more than one answer is possible, then other questions arise about the representation of diversity.

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2. Would it enrich the debate or the analysis to visualize heterogeneity or contrasts? (if so, prefer disaggregated forms ; if not, prefer the most aggregated forms, which are generally more easy to handle)
3. Which forms would help users with the elaboration of their value judgment and make comparisons possible? Between this question and the previous one, a tension might exist. In such cases, developing two indicators, one in an aggregated form and one in a disaggregated form, could allow their concurrent use and stimulate discussions among users and social learning[2].
4. If a value judgment appears difficult to access, is the information provided still useful, at least to understand the limitations of the indicator? (if not, the indicator should probably be discarded).

6. Conclusion

Using indicators to assess sustainability within a governance context requires producing them without knowing who will use them and how. This context also entails considering the ability of indicators to foster the expression and confrontation of multiple viewpoints (i.e., their normative quality) and not only their ability to accurately describe situations or processes (i.e., their descriptive quality). Involvement of multiple actors and iterations between the steps of identification, development, and use of indicators is therefore preferred. It is not always possible to perform iterations, however, for instance due to a lack of time, data or knowledge (from developers or potential users) or to the cost of developing certain indicators. In these cases, indicator developers have greater leeway in shaping indicators and therefore the descriptions and judgments the indicators will generate.

Indicator development, a stepwise process of coding information, is rarely described in the literature on sustainability assessment. We clarified the processing steps required to develop indicators: formalization, estimation, and customization. We used a case study on water management to investigate spatial aggregation, which is a specific customization process common to most landscape-scale or regional sustainability assessments.

Spatial aggregation, the process of changing fine-resolution data into coarser-resolution data to derive meaningful information, partly has a descriptive function. Accordingly, choices are made to increase indicators' ease of use, which generally leads towards aggregated forms (ultimately a

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[2] Although in this article we do not report on the use of indicators but on their development, our experience showed how stimulating it can be to provide stakeholders with two indicators resulting from different aggregation choices. For example, the two indicators presented in Fig. 2, which are based on the same raw data, were used in evaluation workshops with stakeholders. Depending on the indicator used, the participants did not formulate the same value judgments and not with the same facility (it was easier with complete aggregation). Also, the diversity of value judgments among stakeholders was much higher and discussions more intensive with the partially aggregated indicator.

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single value), and scientific soundness, which may lead towards aggregation or not. However, normative considerations can disrupt aggregation choices. These normative claims argue mainly for disaggregated forms of indicators because aggregation then becomes “user-led”, promoting expression of social incommensurabilities. Indicators can be aggregated, however, to limit expression of users’ individual interests.

When descriptive and normative claims are considered together, aggregation choices become more complex and leave more room for developer subjectivity. Completely aggregated forms (single values) do not guarantee that an indicator will be “good for describing” and “good for debating”. Leaving indicators in disaggregated forms, however, is not necessarily the best solution either, even for sustainability problems with a structuring spatial dimension. Spatial aggregation choices illustrate tension between the need for consistency and the need to represent diversity. In this respect, the spectrum of indicator forms (e.g., differing degrees of aggregation, different shapes) merits attention in the practice and theory of sustainability assessments.

Acknowledgement

This research is part of a PhD project funded by the French Ministry of Higher Education and Research. We would like to thank the people we interviewed (stakeholders and experts) to build the database of indicator profiles, Michelle and Michael Corson for proofreading this manuscript and two anonymous reviewers for their comments especially helpful to link the theory about indicators and our experience from the case study.

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