On the spatial aggregation of ecosystem condition indicators

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Abstract

Ecosystem condition assessments (ECA) and accounts use variables and indicators to describe key ecosystem characteristics reflecting the ecosystem condition and any potential deviations from a reference condition. These metrices are rutinely aggregation spatially to produce values representing the condition of a larger area, such as a country. However, we experience little awareness about the potential pitfals arising from aggregation bias of highly modified indicators. Here we outline some consequences regarding the order of the steps involed in normalising variables and aggregating them in space. We show that the choice of aggregation pathways in non-trivial and has the potential to undermine the credibility and precition in ECAs, and to confuse the communication of their results. We introduce a common terminology for aggregation pathways, spesific to ecosystem condition indicators following SEEA EA standards, and make some recomendations about which pathway to use in different settings, and how to report these choices.

Keywords: SEEA EA, ecosystem condition, ecosystem accounting, indicators, aggregation bias

1. Introduction

In ecosystem accounting (EA), fine-scale ecological information is routinely aggregated in space to produce single parameter estimates for entire regions. This simplification is necessary to show major changes in the extent and condition of ecosystems at a scale that is relevant for decision makers. The spatial aggregation of data can lead to biases arising from a number of sources, such as uneven sampling efforts, unequal sampling designs. In ecosystem condition accounting (ECA) specifically, the aggregation of both variables and their normative indicators is common practice and raises the issue of aggregation bias when variables have nonlinear relationships to the normalised indicators[1], which they typically do. The first two sources of error are usually explicitly addressed and managed, but the last case of aggregation bias is often overlooked. In the statistical standard for EAs and the recommended guidelines for ecosystem accounts[2,3], there is no mention of aggregation bias, and there seems to be little awareness in general of the ramification of choosing the wrong spatial aggregation method for variables. Note that it is common in this field to use the term aggregation about the process of aggregating normalised indicators into indices (a thematic aggregation), but in this paper we are discussing spatial aggregation only.

Variables in ecosystem condition terminology are metrics describing ecosystem characteristics[2]. They have a spatial component, tying them to concrete areas, which can be of varying size, from single pixels to entire regions. Variables can be spatially aggregated, for example by taking the sum or an area-weighted mean, to produce variable estimates for larger regions, such as the entire Ecosystem Accounting Area (EAA). Variables

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can also be normalised and turned into normative indicators for ecosystem condition. The mathematical part of this normalisation contains two, sometimes three, steps Figure 1. These steps can be performed simultaneously, but for clarity we discuss them as separate steps. The order of these steps can also change. Variable can be scaled using at least two reference levels, defining variable values to be coded as zero (X_0) or one (X_{100}) on the indicator scale. Variables can be truncated to produce a bound indicator scale between 0 and 1. Sometimes variables are transformed to adjust the indicator scale to reflect potentially nonlinear relationships between the variable and ecosystem condition. This is commonly done by anchoring specific variable values to predefined class boundaries[4], but may also be done without any additional reference levels, for example by using a sigmoid or exponential transformation. When a variable is normalised in this way, its interpretation changes from descriptive to normative. The ecological significance of the indicator might also differ from that of the variable since additional ecological knowledge can be introduced via the reference levels. The indicator is a function of the variable and the reference values, and this relationship is almost always nonlinear (e.g. due to truncation which is ubiquitous practice).

Similar to variables, the reference values used for normalising the variables also have a spatial assignment, but it can be different from that of the variable. For example, variable values may exist for unique 10×10m grid cells, but the reference values may be created with a different spatial scale in mind, for example municipalities, or they can be uniform across the entire EAA (e.g. a natural zero). A major determinant of the resulting aggregation bias from the spatial aggregation of ecosystem condition indicators (Figure 2; Figure 3), is the choice about the order of the different steps in the normalisation and aggregation process, i.e. the aggregation pathway (Figure 4).

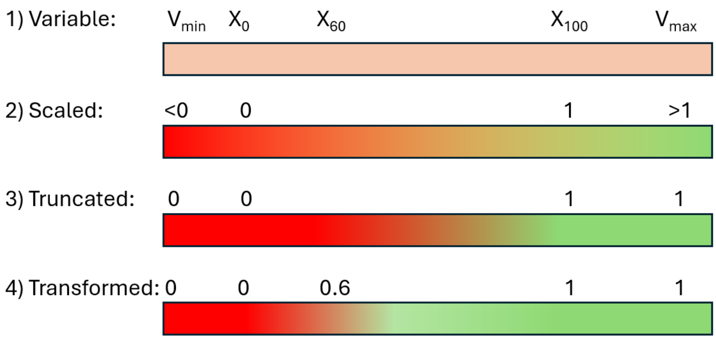

Figure 1: Examples of how important terms are used in this manuscript. Note that the meaning of the terms may differ from how they are used in other fields, such as mathematics. The variable (1), in raw biophysical units, has a minimum and a maximum value (V), as well as points anchoring it to the indicator scale (X). Scaled variables (2) are scaled based on X_0 and X_{100} only. Truncation (3) implies assigning the value of 0 to values below X_0, and the value 1 to value above X_{100}. Transformation refers to the non-linear transformation of values within the 0-1 range, as in this piecewise-linear example by mapping X_{60} to 0.6 on the indicator scale. Transformations without anchoring points are also included in this term, such as exponential or sigmoid transformation. Although both truncation and scaling can be seen as types of transformations, we exclude these methods from the definition here. Examples 2, 3, and 4 are normative (hence the gradient colour scale from red to green) because we assume they have declared that one end of the variable scale represents a good state and the other a poor state. All variables that are treated so that they conform to the definition of indicators in the SEEA EA are said to be normalised. For example, if a truncated variable is assumed to have a linear relationship with the indicator scale, then this variable has been normalised even though it has not been transformed. The term rescale is a synonym to normalise, but we will only use the latter from here on.

2. Why do we normalise?

Normalisation of ecosystem condition indicators, as defined in Figure 1, serves multiple purposes. Firstly, it gives a normative interpretation of a variable, defining a good and a bad state and a directionality to say when something is getting better or worse over time[5]. Secondly, normalisation sets a limit to how much a high indicator value in one place can compensate for a low value somewhere else, and vice versa. This is because truncation effectively means that when we spatially aggregate an indicator, we are always aggregating the negative deviation from the reference levels, and positive deviations (which could compensate for the negative ones) are ignored. Transformation can sometimes also have this effect, e.g. sigmoid transformations. One reason to want to aggregate the negative deviations only, is because the reference levels are set (or should be set) so that values above these limits do not represent any further increase (or decrease) in ecosystem condition. (An exception if the WFD; see Section 3.4). Therefore, this way of aggregation summarises the estimated ecosystem condition (which is generally what we want), and not the variable itself. In other words, we normalise in order to facilitate the spatial (i.e. horizontal) aggregation of our ecosystem condition estimates (i.e. the indicator values), and not merely the variable values. Thirdly, we normalise in order to standardise the indicator on the same scale so that we can perform thematic (i.e. vertical) aggregation. This is commonly referred to as the reason for normalising variables, but as we have shown, it is but one of three main reasons, and also perhaps the least confusing part for many.

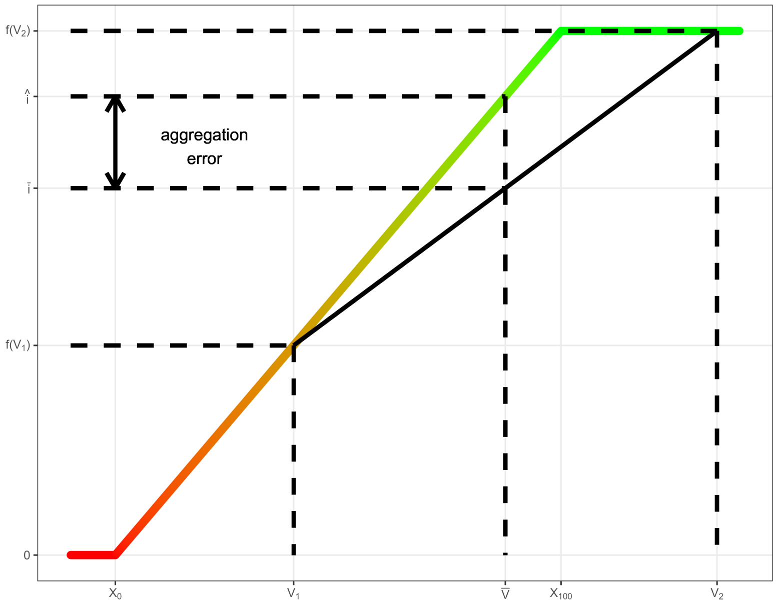

Figure 2: Example showing the difference in indicator values (y-axis) obtained from taking the mean of two variable values (V1 and V1) that are on the original scale (i hat) or on the normalised indicator scale (i bar). Due to truncation at x100, the latter results in a comparatively lower indicator value. The solid coloured line represents the normalisation function f(V). V = variable value, i = indicator value. Modified from Rastsetter (1991).

3. Aggregation pathways

We introduce the term aggregation pathway to describe the order of the steps used to go from a spatially explicit variable to a spatially aggregated metric, usually an indicator. In Figure 4 we show some aggregation pathways that we have come across, and some that we we see as potential new pathways.

Pathway 1 involves early normalisation suing the perhaps most common order of the three steps scaling, truncating and transforming. The three steps may be done simultaneously as well. Then the indicator is spatially aggregated. Pathway 2 involves aggregating the variable before normalising. Pathway 3 is similar, but here there are two aggregation steps: one before and one after normalisation. This can for example be the case when variables are aggregated to the scale corresponding to the reference levels before they can be normalised. Pathway 4 illustrated the aggregation of a variable, with no normalisation. This is the pathway commonly used for variable accounts in the SEE EA. Pathway 5 is a common pathway in the WFD, which does not include spatial aggregation of indicator values. Instead one report the number of water bodies in

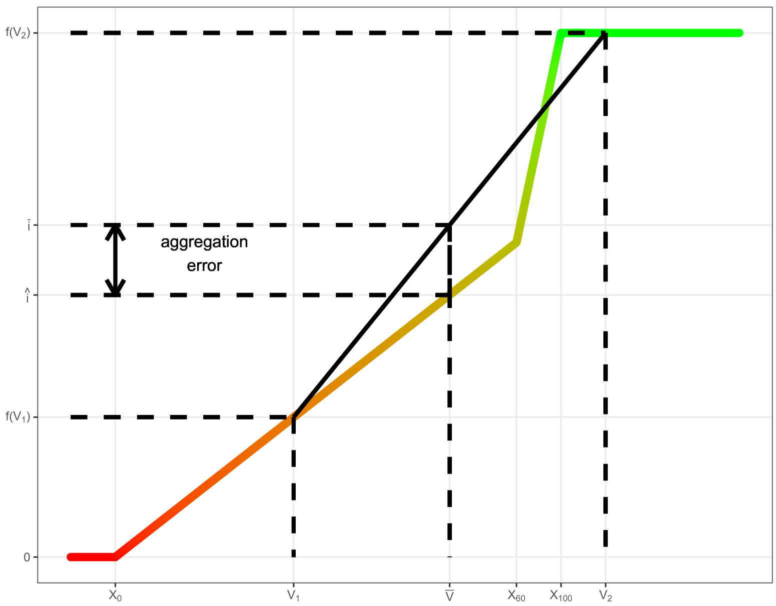

Figure 3: Same figure as above, but showing an example where the normalisation function includes a transformation step (see Figure 1 for definition) that anchors X60 to 0.6 on the indicator scale.

each condition class (spatial statistics). Pathway 6 is a suggested pathway for handling WFD indicator in ECAs (see Section 3.4).

Pathways 7-8 describe the spatial aggregation of multiple indicators, as they all start with the normalisation step. These are not the main topic of this paper, but are included here for completeness. In pathway 7, indicators are thematically aggregated to an index, which is then again aggregated spatially. In pathway 8, spatial aggregation is only done on individual indicators. The two pathways differ in how they handle more complicated schemes for weighted averages, with pathway 8 being more flexible, but it may interfere with the principle of commutativity[2].

Pathway 9 describe how a single indicators is aggregated hierarchically from region to region, whereas pathway 10 shows a case were the aggregation process always starts from scratch for each hierarchical spatial level. As for pathways 7 and 8, pathway 9 and 10 differ in how they propagate the indicator weight (typically area weight) between regions.

The choice about which pathway to use is not trivial, and in this paper we want to highlight some of the issues that could arise from having an *ad hoc* approach to these considerations. Here we go through selected examples to illustrate some common pitfalls.

3.1. Wolves example

Variable: Number of wolves en each carnivore management area (CMA).

Reference: X_0 = is zero wolves present. X_{100}= Number of wolves equal to what experts think the ecosystem would support under the reference condition. The reference levels are unique to each (CMA).

This example is from Norway, where wolves are extinct in most of the country. Therefore, most carnivore management areas will get an indicator value of 0. Wolves exists i designated wolf zones in south-east Norway, although in small numbers. In the Norwegian Nature Index[6], the variable follows pathway 1 and is normalised at the CMA level. When aggregating the indicator to a national value, it is common for the general public to interpret this value as the status for wolves in Norway, and to connect this value to

Norway's international obligations to maintain wolf numbers. But note that even an unlimited number of wolves in the wolf zone would not to bring the national indicator value up to a level indicator good condition. This is because the normalisation process truncates the variable, and does not allow overshooting values to compensate for lower values in the rest of the country.

Conclusion: Indicators should make intuitive sense to the readers. However, there are sometimes good reasons for making things complicated. In this example, The Norwegian Nature Index uses the same pathway for all indicators, so this common misunderstandings about what indicator values represents can be explain just one time, and not for each indicator specifically. It can also be a good idea to sometime go back to the variable, and see if it can be defined differently to avoid these kinds of confusions. Wolf numbers could in this example be converted to wolf density.

3.2. Billberry example

This example illustrates a variable normalised at plot level or aggregated to regions first. At what scale is the ref value intended?

Variable: Horizontal coverage (vertical projection) of billberry (*Vaccinum myrtillus*) recorded in permanent vegetation plots.

Reference levels: X_{100} was defined for each of 5 regions in Norway based on an expert elicitation. Experts were informed by the distribution of the variable values both within and outside protected areas, and the regional distribution of major forest types. They also used their general knowledge about the effect of forestry and on the general vegetation structure of old-growth forests.

The special thing about the billberry indicator is the different spatial resolution for the variable and for the reference level. The variable is recorded at the scale of vegetation plots. The reference level however, is designed with a regional spatial scale in mind, especially because of how it encompasses the known variation in forest types in a region to estimate the mean billberry coverage under the reference condition. Because the normalisation includes a truncation step, scaling the variable at the plot scale (pathway 1; Figure 2) would not allow overshooting values to compensate for lower values when aggregating regional indicator values, which would then be negatively displaced ($\bar{i}$) relative to when aggregating variable values ($\hat{i}$; Figure 2). Scaling at the plot scale would require require unique reference levels for each forest type. However, both pathway 1 and 3 has been used for this variable in two different forest ecosystem condition assessments. Due to non-negligeable truncation of the variable during the normalisation, the two indicators were subject to different levels of aggregation bias, and consequently the spatially aggregated indicator values for the two assessments became different. This cause a general confusion about how how the same variable (and the same date) can produce different indicator values.

Conclusion: Given that the reference value is the way it is, this indicator should have followed pathway 3, and spatially aggregated the variable, from plot scale to regional scale, before normalising the variable and potentially aggregating it further. It would also be possible to use pathway 6.

The wolves example also highlight the importance of making clear the differences in the interpretation of variables and indicators. Often indicators and variables are both included side-by-side in ecosystem condition assessments/accounts. This is also recommended practice following the SEEA EA. However, if the indicators that are presented are normalised before any spatial aggregation, then the interpretation of the indicators is not simply as a normalised version of the variable. Indicators typically now reflect the average ecosystem condition, where areas in very good or very poor condition have limited ability to compensate for opposite extreme values elsewhere. The spatially aggregated variable on the other hand, may reflect something like a sum of individuals, or some other aspect where values above and below the average value are able to compensate for each other.

3.3. Alien species example

Variable: The local ecological effect from alien species (mostly vascular plants) recorded on a 7-step ordinal scale (1 = no alien species, 7 = only alien species). The data comes from nature type monitoring with reference to individual occurrences (polygons).

Reference levels: X_0 = total dominance from alien species (variable value 7). X_{100} = zero influence from alien species (variable value 1). X_{60} = ~2-5% alien plant cover (variable value 3).

In this example, the reference levels are uniform throughout the EAA, and the normalisation includes a transformation in the form of a piecewise-linear transformation by anchoring X_{60} to 0.6 on the indicator scale. When performing an ECA, one has the option to either aggregate variable value for each region (each ecosystem asset), and then normalise that value (pathway 2 and 3), or to normalise the variable at the scale of the original nature type polygons, and then aggregate the indicator values to the regional level (pathway 1).

Conclusion: One benefit of early normalisation is that two nested assessments, such as one national, and one assessment of region Y inside the same country, will get the same spatially aggregated value for region Y. The other thing to ask oneself here is: *Why do we normalise* in the first place (Section 2)? One reason is that we want to summarise information in space about the ecosystem condition. It is the indicator values that hold this information, and not the variable. We would therefore favor pathway 1 for this example.

Separate assessments should give identical indicator values for the same areas, given the same underlying data. When this is not true it raises concerns about reproducibility and sacrifices the credibility of both assessments. This was also the case in the billberry example, but here we used another example to illustrate the point further.

3.4. Phytoplankton trophic index (PTI)

Variable: Mean score of algal species present, based on a set of indicator species scored for phosphorus requirements/tolerance. The variable is recorded in water bodies (lakes of 0,5 km^2 or more).

Reference levels: X_{100} = median variable value for water bodies in reference condition. X_0, X_{20}, X_{40}, X_{60} and X_{80} = intercalibrated threshold values, based on dose–response curves.

For use in water management, the Water Framework Directive (WFD) indicators uses aggregation pathway 7 Figure 4, with truncation, scaling, and transformation. The value obtained after the first two steps is called an EQR (ecological quality ratio), and the value obtained after the third step nEQR (normalised EQR). Spatial aggregation is not done for the WFD, and therefore aggregation bias is not an issue. When WFD data are put into use in other contexts, however, aggregation becomes important.

Conclusion: Because of how X_{100} is defined based on the median value across reference lakes, overshooting values ($> X_{100}$) should be preserved in the spatial aggregation. Otherwise we get a negative displacement, as in the bilberry example. This means that neither EQR values (which are untransformed), nor nEQR values (which are truncated), can be used uncritically in ECAs. One solution, to enable the use of WFD indicators in ECA, would be to change to pathway 6, with (1) scaling, (2) transforming, (3) aggregating and (4) truncating the values[?] . Furthermore, Eurostat **(author?)** [7]
encourages reporting of variable values. These, however, cannot be aggregated spatially in a meaningful way.

4. Recommendation

Based on the example above, we suggest some recommendations for developers of ecosystem condition indicators and assessment for trying to avoid some of the pitfalls from having a too casual approach to the choice of aggregation pathways.

1. Report the aggregation pathway, using standardised terminology

In indicator documentation or ECA reports, authors should make an effort to make a precise description of the steps in the aggregation process. To do this we suggest using the terms as described in Figure 1. The description can be made even easier by referencing specific aggregation pathways in Figure 4 by number.

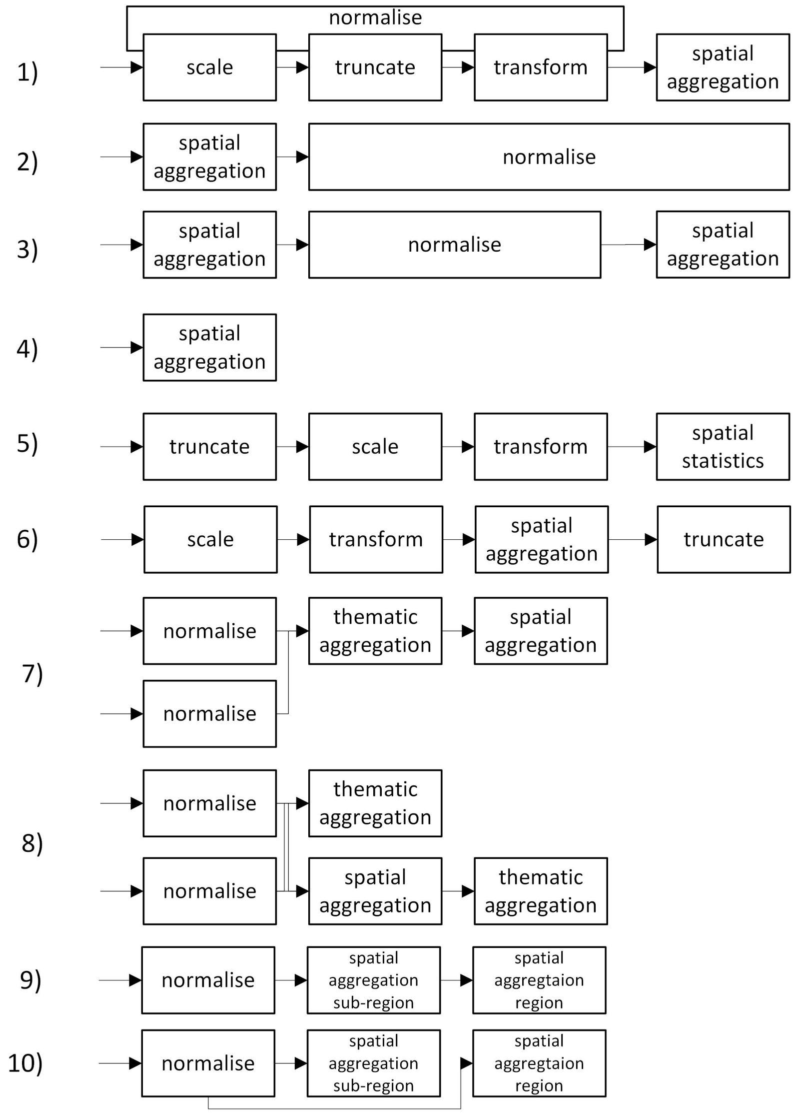

Figure 4: Flowchart showing pathways for the spatial aggregation of variables in ecosystem condition accounting. Normalisation refers to the steps that make a variable conform to the definition of an indicator in SEEA EA, which may or may not include the transformation step. A truncated and/or transformed variable will have a different interpretation than the original variable. The aggregation bias depends on whether variables are truncated and/or transformed variables before or after spatial aggregation. Variables are never normalised (pathway 4), and hence the aggregation bias for variables will be different than for indicators. An important factor influencing the the choice whether to normalise early (as in pathway 1), or later, is the spatial validity of the reference levels, and sometimes raw variable values (e.g. billberry coverage in vegetation quadrats) are spatially aggregated to the scale that was considered when setting the reference levels (e.g. average regional billberry coverage).

Besides making the indicator workflow itself more transparent and reproducible, ee believe this recommendation would help raise the general awareness about aggregation bias in EAs, both among readers and researchers. It will make the interpretation of assessment less prone to misunderstanding. It will also make troubleshooting easier, as i the billberry example where researchers had to spend several days looking though old code to identify the reason why two assessment produces dissimilar indicator values from the same underlying data.

2. Normalise variables early, but at the scale where the reference levels are relevant

Normalising variables early in the aggregation pathway has several benefits, such as comparability between nested assessments (Section 3.3). It also means that you are aggregating normative measures of condition, which is generally what you want in ECAs. But same as variables and indicators, reference levels also have a spatial resolution, and they should only be used to normalise variables when the variable is at a scale which is relevant to the way the reference levels are defined. This was exemplified with the billberry example (Section 3.2).

3. Use the same aggregation pathway for all indicators in the same assessment

It may be premature, or not even possible, to prescribe an aggregation pathway to be used for all ECAs, but internal consistency within assessments should be possible. As we saw in the wolves example (Section 3.1), this eases interpretation and reduces the chance that the meaning of indicators are misunderstood.

4. Use unique indicator IDs on indicators that are similar, but use different pathways

Indicators (and variables) often exist in multiple version, varying slightly in the raw data or in the methods used to produce the data or metrics. Yet different versions are often refereed to by the same common name. This causes confusion about which indicator version is being used, and thus making it difficult to make out which aggregation pathway that has been used. We recommend making use of stable indicator IDs, unique for each version of the indicators sharing the same common name. This has for example been implemented in ecRxiv, a publishing platform for ecosystem condition indicators.

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