

¹ On the spatial aggregation of condition metrics for ecosystem accounting

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³ **Abstract**

In face of the ongoing nature crisis, the international community is setting targets and deciding on actions to combat the current biodiversity crises. For this to be effective they need tools to accurately describe the current situation and to monitor trends in ecosystems over time. Ecosystem condition accounts (ECA) is one such tool that use variables and indicators to describe key ecosystem characteristics, reflecting their condition and deviations from a reference condition. Because the purpose is to inform decisions at relatively high political levels, these metrics are often spatially aggregated to represent larger areas, such as countries. However, spatial aggregation of information has the potential to alter the descriptive and normative interpretations one can make from these metrics. For example, aggregation displacement causes the information held in variables and indicators to diverge when these are aggregated spatially. This process is influenced also by the order of steps involved in normalising and aggregating variables, i.e. the aggregation pathway. Although aggregation displacement and the type of aggregation pathway chosen for the indicator clearly impact both the indicator values and their interpretation, there are no clear guidelines or deliberation on these topics in the SEEA EA standard for ecosystem accounting. This paper outlines the consequences of different aggregation pathways, emphasising their impact on the credibility of ECAs, and how these are interpreted by users. We introduce a standardised terminology for aggregation pathways specific to ecosystem condition indicators following the SEEA EA standard and provide recommendations for selecting appropriate pathways in various contexts. Our discussion of this topic is aimed at raising the general awareness of spatial aggregation issues and to guide indicator developers in choosing and reporting spatial aggregation methods.

⁴ **Keywords:** SEEA EA, ecosystem condition, ecosystem accounting, indicators, aggregation bias,
⁵ aggregation error, aggregation displacement, upscaling

⁶ **1. Introduction**

⁷ The world is facing a nature crisis of a magnitude that requires urgent political decision making and
⁸ international coordination (IPBES, 2019). Ecosystem accounting has been fronted as a framework for
⁹ providing a knowledge base for this (Bagstad et al., 2021; Grondard et al., 2021). Ecosystem accounts are
¹⁰ environmental assessments aimed at communicating on the status and trends in the extent and condition of
¹¹ ecosystems at a scale and in a format that is relevant for decision makers (Edens et al., 2022; Comte et al.,
¹² 2022). For ecosystem condition accounting (ECA) and assessments, this often requires that **metrics** (terms
¹³ in bold are explained in Table 1) used to describe the condition of ecosystems are **aggregated spatially** to
¹⁴ produce a single value for a larger area. This represents a type of knowledge synthesis, aimed at condensing
¹⁵ the complexity of the real world into something that is relevant to decision makers and potentially actionable

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16 at a political level ([King et al., 2024](#)). However, the way spatial aggregation is done affects how a metric
17 should be interpreted, and the descriptive properties and normative claims one can make based on it ([Allain](#)
18 [et al., 2018](#)). Without an understanding of the pitfalls during spatial aggregation of information, one risks
19 introducing unintended and undetected systematic bias into the decision making process.

20 Although much attention has been devoted to the **vertical aggregation** of environmental indicators
21 into composite **indices** (e.g. [Langhans et al., 2014](#); [Maes et al., 2020](#); [Union/EC-JRC, 2008](#)), as well as
22 to the spatial aggregation of relatively unmodified or raw **variables** (e.g. [Allain et al., 2018](#)), there is a
23 lack of explicit deliberation on the special case of spatially aggregating highly modified **indicators** used for
24 ecosystem condition accounting (but see [van Beurden and Douven, 1999](#)). This paper therefore focuses on
25 explaining and providing guidelines for the spatial aggregation of ecosystem indicators in the context of the
26 System of Environmental Economic Accounting - Ecosystem Accounting (SEEA EA) ([United Nations, 2024](#))
27 - the most used ecosystem accounting framework in the world ([Comte et al., 2022](#)). There is a jungle of
28 terms for the topics of indicators and aggregation, which are used inconsistently across scientific fields and
29 different frameworks for ecosystem assessments, and there is a clear need for a standardised terminology,
30 at least with the SEEA EA field of practice. This study goes some way towards this by including a list of
31 terms and their definitions in Table 1 and by suggesting a new reporting terminology for the different steps
32 in spatial aggregation, i.e. the **aggregation pathway**.

33 SEEA EA includes principles for compiling accounts for ecosystem extent, ecosystem condition, and ecosystem
34 services ([United Nations, 2024; 2022](#)). We will focus on the SEEA EA condition accounts in this paper,
35 although spatial aggregation is also a relevant topic for the other parts of the account, and for other types of
36 indicator-based ecosystem assessments. In 2026, EU and EEA countries will be required to report ecosystem
37 condition accounts to Eurostat and the European Commission ([European Council and Parliament, 2024](#)),
38 and these accounts will have to be spatially aggregated to national levels. This underlines the importance
39 of having a robust methodological framework for the spatial aggregation of data and information.

40 This paper is aimed primarily at indicator developers to provide them with recommendations for how
41 to choose the best aggregation pathway for variables and indicators, and how to report these choices in
42 an accessible and transparent way. Indicator developer subjectivity affects indicator interpretation ([Allain](#)
43 [et al., 2018](#)) and thus ultimately the conclusion from ECAs. Still, the process of designing indicators and
44 estimating indicator values is often left entirely to them, with little real involvement from indicator users,
45 such as regional and local land managers and policy makers. It is therefore important to be aware of the
46 role that indicator developers play in shaping the type of information and the narratives that are presented
47 to decision makers. We use three examples to illustrate some of the effects arising from choosing different
48 aggregation pathways.

Table 1: Key terms and concepts as they are used in this paper.

Term or concept	Definition and deliberation
Variables, indicators and metrics	We use the SEEA EA definitions of the terms variables, indicators (normalised variables) and metrics (referring to either a variable or an indicator) (United Nations 2024). Variables are typically either in percentages or fractions, or as raw biophysical units, such as biomass or density. Indicators, on the other hand, are always on a unitless scale between 0 and 1, where 0 represents very poor (or the worst possible) condition, and 1 represents very good (or the best possible) condition. Sometimes indicators are calculated directly (e.g. Åström and Kolstad 2025), but usually indicators are made by normalising variables based on two or more reference levels (United Nations 2024 , sec. 5.60).
Reference condition (RC)	Reference condition is the state or condition of the ecosystem that we want to compare the current state against. It can be a purely theoretical construct or a real historical state. It does not need to be defined with any real data.

Term or concept	Definition and deliberation
Reference levels (RL)	Reference levels (also called reference values) are variable values that act as anchoring points to specific values on the indicator scale, and are used to convert variables into indicators. This definition is different from that in SEEA EA, but at least conceptually it is the same. There can be from two to many RLs per indicator and they are distinguished with a special nomenclature X_n where n is the corresponding indicator value times 100. For example, X_0 and X_{100} refer to variable values coded as 0 or 1 on the indicator scale, respectively (sometimes called the lower and upper RLs). The X_{60} can hold a special meaning if, like in the WFD and in some applications of SEEA EA, the value 0.6 on the indicator scale represents the boundary or threshold between good and reduced condition. Defining X_{60} , or any RL other than X_0 and X_{100} , is one way to quantitatively describe a non-linear relationship between the variable and ecosystem condition (referred to as <i>Transformation</i>).
Normalisation	This is the mathematical process of turning a condition variable into an indicator <i>sensu</i> SEEA EA. It consists of three distinct steps: scaling, truncation, and transformation. Scaling a variable means to recode a variable to a unitless unbound scale based on two reference levels, a lower (X_0) and an upper (X_{100}), that define the variable values to be coded as zero and one on the indicator scale, respectively. Truncation means to recode scaled variable above 1 to become 1, and values below 0 to become 0. Transformation means 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 [<i>sensu</i> WFD; EU (2000)] which we call reference levels (Czucz et al. in prep; Jakobsson et al. 2020), but may also be done without explicit reference levels, for example by using a sigmoid or exponential transformation (Mienna and Venter 2024). Normalisation is frequently referred to as rescaling in the SEEA EA literature, but we avoid this terms because of the need to provide better differentiation between the three steps of the normalisation process, where scaling is one of them. Also, in a parallel terminology, normalisation can be considered modeling, and spatial aggregation before and after normalisation can be referred to as pre or post processing, respectively (Beurden and Douven 1999).
Categorisation	Means to divide the indicator scale into discrete fractions, either based on reference levels, or some other rule (e.g. equal range for each class).
Aggregation displacement	Referring to the systematic shift that occurs to the relative values of variables and their corresponding indicators when they are spatially aggregated. When we take the average of two variables, each of which have attribute values (i.e. indicator values) associated with them via some non-linear function (e.g. truncation or transformation), then the attribute of the average variable value differs from the average of the attributes of the original variable. Rastetter et al. (1992) referred to this as aggregation error and used it to describe some of the dangers associated with upscaling in the sense of using precise fine-scale information to explain or predict large scale phenomena. However, in ECAs, the difference between variables and indicators is an intentional one, and we therefore choose to refer to what is essentially the same mathematical phenomenon with the less derogatory term aggregation displacement.

Term or concept	Definition and deliberation
Spatial aggregation	Spatial (sometimes called horizontal) aggregation is the process of summarising data from different sub-areas and taking this new value as the value for all constituent sub-areas. It means going from fine-resolution data to less fine or coarse resolution data. In related fields of study this operation may be described as <i>increasing the support</i> or <i>reducing the grain</i> (Bierkens, Finke, and Willigen 2002). Aggregation can be partial, resulting in two or more spatial areas with unique values, or total, if it results in just a single number summarising all the data. Different summary functions can be used, including the area-weighted arithmetic mean, which is required under when aggregation indicator values in SEEA EA. The term <i>upscaleing</i> is sometimes used synonymously to our definition of spatial aggregation, but it also has a wider definition tied to the ambiguous use of the terms scale to mean either grain or extent. It's common to lump spatial aggregation together with some types of extra- or interpolation operation, such as averaging point data and attributing this value to entire polygons (Gruijter and Braak 1990), or spatial estimation methods (e.g. geostatistics) and subsequent spatial sampling (D. J. Brus and Gruijter 1997). However, for the detailed deliberation in this study it is important to note the distinction between these.
Temporal aggregation	Refers to operations involved in combining data from different time points or periods to represent a single temporal period (e.g. an accounting period or a growing season).
Thematic aggregation	Also called vertical aggregation. In the case of ECA, this refers to an aggregation of two or more indicators into a composite index (<i>plural: indices</i>).
Spatial prediction	It refers to any estimation of the value of a variable at an unobserved location, and therefore include both inter- and extrapolation. Interpolation means to <i>fill in the gaps</i> , or to increase the density of the data. Extrapolation means to expand the spatial extent of the data or beyond the current data range. There is often no clear boundary between these two operations when applied in ECA as an area may for example be within the geographical range of the current data, but outside the environmental range. Many different methods are employed for spatial predictions within ECAs, such as statistical models (e.g. regression models) or geostatistical models (e.g. kriging). These methods are more or less sophisticated ways to essentially <i>spread</i> or learn from the available data to give values to areas where there is no data. This is distinct from the process and purpose of spatial aggregation, which seeks to simplify data.
Design-based and model based prediction	These are two fundamentally different ways of doing and thinking about spatial and statistical prediction. Design-based approaches relies on classical sampling theory and uses what is known about the sampling design to make spatial inferences. It is generally applied in more simple ways, such as with look-up tables, but model-assisted estimation using statistical models is also possible. Design-based approaches produce things like the sample mean and sample variance and assumes the sampled values are correct (fixed), and uncertainty arises due to where we chose to sample (the locations are random). Model-based prediction uses geostatistical models, such as kriging and produces estimates such as the model mean or model variance. In this framework, the locations are considered fixed and the uncertainty arises due in the statistical model. Readers are referred to Dick J. Brus (2021) for more details.
Ecosystem assets and ecosystem accounting areas	Ecosystem assets in SEEA EA are the smallest spatial units for which information is sought, made up of contiguous spaces of a specific ecosystem type. The ecosystem accounting area is the ' <i>geographical territory for which an ecosystem account is compiled</i> ' (United Nations 2024)

Term or concept	Definition and deliberation
The ecological fallacy	The ecological fallacy (Robinson 2009) is the error of assuming that relationships or patterns observed for groups (at the aggregate level) must also hold true for the individuals within those groups. In EA, aggregated data will mask differences within regions and lead some people to interpret this as regions being more homogenous than they really are.
The Modifiable Area Unit Problem (MAUP)	MAUP describes the sensitivity of spatially aggregated information to the choice of spatial units used for data collection or aggregation Wong (2009). These units can be arbitrary (<i>modifiable</i>), and different sizes and configuration of units can have large effects on the outcome of aggregation.
Spatial compensation	In this context, spatial compensation refers specifically to the ability of variable values above X_{100} in some areas to compensate for values below X_{100} elsewhere (assuming here that $X_0 < X_{100}$). Whether or not to allow spatial compensation in spatial aggregation has a large impact on the value and interpretation of indicator values.
Post-stratification	A statistical technique used to correct for a biased sample by forcing the sample to match the main population in some key characteristics. In ECAs it is common to have data that lack a clear probability based sampling design, and therefore end up with more samples from certain strata (e.g. some geographic region or within some shared environmental condition). Post-stratification seeks to remove this unevenness in the <i>post-processing</i> , e.g. by doing a step-wise spatial aggregation via the same strata.

49 2. Reasons for normalising variables

50 Normalisation of ecosystem condition indicators serves at least three purposes. Firstly, it gives a normative
 51 interpretation of a variable, defining a good and a bad state, and simultaneously a directionality to say
 52 when something is getting better or worse over time (Czúcz et al., 2021). Although some variables may
 53 have normative properties (due to decisions about how they are chosen, defined, aggregated or presented
 54 (Allain et al., 2018)), the **normalisation** of variables into indicators makes them explicitly normative by
 55 introducing a clear directional interpretation, where increasing values always refer to an increase in condition
 56 in the direction of a **reference condition**. The mathematical part of this normalisation contains several
 57 steps (Figure 1). Two or more **reference levels** are needed to convert variables into indicators.

58 Secondly, normalisation sets a limit to how much a high variable value in one place can **compensate** for
 59 a low value somewhere else, and vice versa (Pedersen et al., 2016). This is because **truncation** effectively
 60 means that when spatially aggregating an indicator, one is always aggregating the negative deviations from
 61 the upper reference level X_{100} , and ignoring any positive deviations which would otherwise compensate for
 62 the negative ones (see **Example 2**). **Transformation** with asymptotes have the same effect as truncation,
 63 e.g. sigmoid transformations. It is important to note that this is by design, i.e. that X_{100} is set (or should be
 64 set) so that values above this limit (assuming $X_{100} > X_0$) do not represent any further increase in ecosystem
 65 condition (for an exception, see **Example 3**). Therefore, aggregation of truncated indicators summarises
 66 the estimated ecosystem condition over an area, and not the variable itself. The flip-side of this is that
 67 spatially aggregating the original variable values does not directly summarise information about ecosystem
 68 condition for that area.

69 Thirdly, we normalise in order to standardise the indicator on the same unitless scale, making them
 70 comparable, so that we can perform thematic (i.e. vertical) aggregation (Jakobsson et al., 2021; United
 71 Nations, 2024, §5.81). This is commonly referred to as *the* reason for normalising variables, not least
 72 because it is perhaps the least confusing one for many; nonetheless, as we have shown, it is not the only
 73 reason.

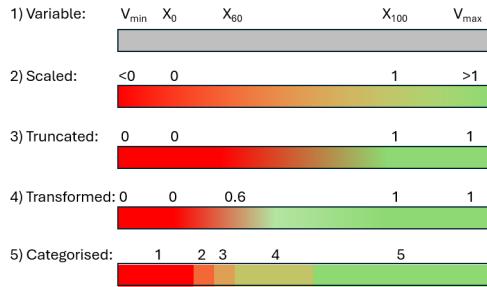


Figure 1: Examples of how important terms are used in this manuscript. Note that the meaning of the terms may differ from how they are used in other fields, such as mathematics. The variable (1), in original units, has a minimum (V_{\min}) and a maximum value (V_{\max}), as well as points anchoring it to the indicator scale (reference levels; X_n). Scaled variables (2) are scaled based on X_0 and X_{100} . Truncation (3) implies assigning the value of 0 to values below X_0 , and the value 1 to value above X_{100} . Transformation (4) 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. Categorisation (5) refers to the creation of discrete bins (here five) where incremental change in uncategorised indicator values within a set of class boundaries is ignored. Although truncation, scaling and categorisation can be seen as types of transformations, we exclude these methods from the definition here. Examples 2-5 are normative (hence the gradient colour scale from red to green) because we assume it has been declared that one end of the 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 only use the latter to avoid confusion with the specific operation of scaling.

74 3. The challenges and rationale for spatial aggregation in ecosystem condition accounting

75 Spatial aggregation of data refers to the conversion of fine-resolution data into coarser-resolution data
 76 and, depending on both the purpose and the nature of the metric, there can be several reasons for both
 77 performing and refraining from spatial aggregation. Readers are referred to [Allain et al. \(2018\)](#) for a more
 78 comprehensive review of different reasons for spatially aggregating variables. As we will illustrate below,
 79 there are several requirements in the SEEA EA that make spatial aggregation necessary.

80 Generally, spatial aggregation increases the clarity and accessibility of a metric because it simplifies or com-
 81 presses the information, sometimes into just a single number (**total aggregation**). This may be necessary
 82 in some cases of ecosystem accounting when information is required at a relatively high administrative level
 83 (e.g. nations) and when variables and indicators need to be presented in standardised tables which don't
 84 allow for describing a lot of spatial variation.

85 Sometimes aggregation of a metric is required for it to actually fit its purpose and become relevant to what
 86 it is designed to describe. For example, a hypothetical variable “*proportion of total land area above critical*
87 nitrogen load”, informed from a spatial map of nitrogen loads, would only make sense if data was aggregated
 88 across some defined area. The reason and need for aggregation may therefore originate in the original idea
 89 for the metric.

90 Data may also be only **partly aggregated**, or the same metric may be presented at different levels of
 91 aggregation ([Allain et al., 2018](#)). A minimum level of aggregation may be decided based on uncertainties in
 92 the data: high spatially resolute data may be imprecise at fine scales, leading to false sense of certainty and
 93 potential misinterpretation ([Lyytimäki et al., 2013](#)), but these same data seen over a larger area may be
 94 assumed to converge on some true value, making spatially aggregated data better suited for communication
 95 to users. Other common arguments for performing spatial aggregation are to ease visualisation and to allow
 96 relevant comparisons ([Allain et al., 2018](#)). For example, ecosystem condition metrics can be visualised on
 97 a map, but when both the spatial resolution and spatial variation is high, maps become too complex, even
 98 unintelligible. It is therefore common to partially aggregate the data and provide a coarser map where
 99 different colours are used to distinguish different values. Similarly, one may choose to aggregate such that

100 the spatial resolution matches some meaningful delineation, notably **ecosystem assets** in SEEA EA, which
101 makes it possible to easily compare the ecosystem condition between these areas.

102 Spatial aggregation of ecosystem condition metrics may also be applied to alleviate issues of spatial auto-
103 correlation. For example, if data is collected opportunistically with sampling sizes or sampling effort varying
104 between areas, then performing partial spatial aggregation to some intermediate-sized, homogeneous areas,
105 will give equal weight or importance to all areas regardless of how many data points are included in each.
106 This approach represents a form of **post-stratification** that is also relevant to process data from hierarchical
107 (e.g. blocked) sampling designs.

108 Spatial aggregation can have several consequences that may or may not be desirable, such as smoothing
109 out spatial variability, which can mask local patterns and trends. This smoothing out makes the data and
110 its inherent information less suitable for some use cases, such as depicting spatial variation that can be used
111 to support local land-use planning, for aiding a debate about spatial conflicts, or for identification of high
112 risk areas ([van Beurden and Douven, 1999](#)).

113 Similar to variables, the reference levels used for normalising variables also have a spatial assignment, which
114 can be different from that of the variable. For example, variable values may exist for unique 10×10 m grid
115 cells, but the reference levels may be created with a different spatial scale in mind, for example municipalities,
116 or they can be uniform across the entire **ecosystem accounting area** (e.g. a natural zero). The bilberry
117 example (**Example 1**) shows that, to ensure variables and reference levels are at a commensurable spatial
118 scale, sometimes variables need to be partly spatially aggregated before they can be normalised.

Example 1 – Bilberry

This example is to show what it means that the variable and the reference levels need to be at a commensurable spatial scale before doing the normalisation.

Variable: Horizontal coverage (vertical projection) of European blueberry or bilberry (*Vaccinium myrtillus*) recorded in permanent vegetation plots.

Reference levels: X_{100} is defined for each ecosystem asset 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. X_0 is a natural zero (bilberry completely absent).

Table 2: Dummy data for the bilberry example. Variable values (% cover of bilberry) are recorded for each vegetation plot, and aggregated (arithmetic mean) to the ecosystem asset (EA) level. The X_{100} value is defined for the EA level, but in this hypothetical case it is also dis-aggregated to each vegetation plot and used for normalising variable values also at the plot level. The dis-aggregated X_{100} values, and subsequent values that rely on these, are marked with an asterisk (*).

	Plot 1	Plot 2	EA
Variable values	2	36	19
X_{100}	20*	20*	20
Indicator values	0.1*	1.0*	0.95 (0.55*)

The bilberry indicator exemplifies different spatial resolutions for the variable and for the reference levels (Table 2). 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 each ecosystem asset to estimate the mean bilberry coverage under the

reference condition. Because the normalisation includes a truncation step, normalising the variable at the plot scale (pathway 1; Figure 2) does not allow overshooting values in plot 2 to compensate for lower values in plot 1 when spatially aggregating the indicator values. When normalising at the plot scale in this case, one is essentially aggregating only the negative deviations from the upper reference level X_{100} , and the aggregated indicator value becomes negatively displaced (0.55) relative to when aggregating variable values (0.9). Given that X_{100} is defined the way it is, this indicator should follow pathway 3 (Table 4) by spatially aggregating the variable from plot scale to ecosystem asset to allow spatial compensation between plots. At the scale of ecosystem assets, the variable and the reference levels are at a commensurable scale, and the variable can be normalised and potentially aggregated further.

120

121 4. Spatial prediction: fitting data to ecosystem assets

122 In SEEA EA, information about ecosystem condition is made spatially explicit by assigning variable or
123 indicator values to ecosystem assets. This process requires some spatial manipulations of data, or scale
124 changes ([Ewert et al., 2011](#)). The type of manipulation depends on the spatial resolution of the underlying
125 data, as well as the size and configuration of the ecosystem assets. To elaborate on this issue we first make a
126 distinction between two main types of data: spatially exhaustive data and sparse (i.e. spatially discontinuous)
127 data.

128 Spatially exhaustive, or wall-to-wall data, include remote sensing products, but also other types of pre-
129 aggregated data, where sparse data are assigned to areal units. This last type of data is very common. A lot
130 of demographic information for example is made available at the scale of administrative units, rather than at
131 the level of individuals (which would be very ineffective and also problematic in terms of protecting sensitive
132 information). Similar pre-aggregation is rather common and present in most complete datasets. Consider, as
133 an example, data from LiDAR (Light Detection And Ranging). The raw data is a point cloud, yet the most
134 commonly available datasets are rasters, such as surface or canopy models, i.e. wall-to-wall generalisations
135 of the point cloud. Also data such as satellite images, or maps derived from such, have some inherent
136 pre-aggregation where values are averaged for each raster cell. Often there is little indicator developers
137 can do to affect this pre-aggregation step, but it is important to be aware of it in light of the **ecological
138 fallacy**. This issue will, for example, hamper the detection of true maximum or minimum values (used in
139 *worst rule* (i.e. one out all out) aggregation, for example in the Water Frame Directive - WFD), since these
140 extremes are already smoothed out in the pre-aggregation step ([van Beurden and Douven, 1999](#)). This will
141 clearly affect the suitability of such data for identifying areas of high risk (very degraded areas, for example).
142 Similar problems can also occur in subsequent aggregation steps of the indicator calculation workflow, and
143 it is important to ensure that the spatial aggregation function used does not have any unintentional effects
144 on the meaning of the metric.

145 Sparse data refers to datasets where variable values are assigned to singular points or isolated small areas.
146 In these cases, there will be a lot of area inside each ecosystem asset for which we have no direct information,
147 and some ecosystem assets may have no data at all. Spatial prediction can be used assign variable or indicator
148 values to all areas (as is required in the SEEA EA framework). Both **design-based** and **model-based**
149 approaches are valid under SEEA EA. Model-based approaches (e.g. interpolation) generally make variables
150 easier to aggregate spatially since the spatial structure of the variables will already be accounted for via
151 the prediction process. For example, if using kriging to create local predictions for a variable across an
152 ecosystem asset, then a simple systematic sampling of the field of values across the ecosystem asset will be
153 valid, and give representative grounds for statistical inference ([Brus, 2021](#)). However, transparency, validity
154 and simplicity are all very desirable properties from ECAs, which favours a design-based approach that
155 makes no modeling assumptions ([Brus, 2021](#)). From here on, we will focus on design-based approaches.

156 For design-based approaches, one can assign values to areas via simple aggregation functions used on data
157 values that fall within a given ecosystem asset. Many aggregation functions are available, such as sum,

158 worst-rule, different percentiles, arithmetic, geometric, or harmonic means ([United Nations, 2024](#), §5.54).
159 In addition, non-parametric bootstrapping ([Kolstad, 2025](#)) and Bayesian updating ([Kolstad et al., 2024](#))
160 can be used to possibly obtain better descriptions of the uncertainty in the estimates. If the inclusion
161 probabilities are known, or they can be estimated, then the Horvitz-Thomson estimator for the sum or
162 the mean (and variance) of a spatial sample is appropriate and useful, especially when the data originated
163 from a stratified sample ([Horvitz and Thompson, 1952](#)). Depending on the random process used to select
164 the sampling points we may need to account for the spatial structure (spatial autocorrelation) of the data
165 when doing this aggregation. This can be addressed in several ways, such as model-assisted approaches
166 ([Brus, 2021](#)), e.g. using regression models ([Brus, 2000](#)). One can also add an intermediate aggregation step
167 via homogeneous areas (domains), ecosystem assets or some smaller basal spatial units, to control for this
168 spatial non-independence, and thus reduce the sampling bias and variance.

169 In our experience, the choice of which area units to use when doing this step-wise aggregation is often not
170 reflected much upon. In some cases the areal units are even decided politically, for example to administrative
171 units, with little ecological justification for this choice. However, this decision clearly affects the results of
172 the spatial aggregation via a well-described (but often forgotten?) statistical problem referred to as the
173 **modifiable area unit problem (MAUP)**. The MAUP can lead to inconsistencies between repeated
174 or nested ECAs, leading to confusion and mistrust. This is unfortunate, as it is important for decision
175 makers to see that the information they are basing their decision on is robust and insensitive to aggregation
176 methods ([van Beurden and Douven, 1999](#)). One option to reduce this discrepancy and arbitrariness is to
177 use ecologically motivated areal units in the step-wise aggregation such as homogeneous ecosystem areas
178 ([Vallecillo et al., 2022](#)) or homogeneous impact areas ([Kolstad et al., 2024](#)).

179 5. Aggregation displacement and spatial compensation

180 [Rastetter et al. \(1992\)](#) showed that when taking the average of two variables, each of which have attribute
181 values (e.g. indicator values) associated with them via some non-linear function, then the attribute of the
182 average variable value differs from the average of the attributes of the original variables. They referred to
183 this as aggregation error and used it to describe some of the dangers associated with **upscaling** in the sense
184 of using precise fine-scale information to explain or predict large scale phenomena. In ECA, the aggregation
185 of both variables and indicators is common practice and raises this issue of aggregation error (Figure 2)
186 when variables have nonlinear relationships to the normalised indicators ([Rastetter et al., 1992](#)), which they
187 typically do. However, in our case, the difference between variables and indicators is an intentional one, and
188 we therefore choose to refer to what is essentially the same mathematical effect with the less derogatory
189 term **aggregation displacement** (Figure 2).

190 Spatial aggregation leads to a divergence in the type of information held in variables and in their associated
191 indicators, to a point where they become qualitatively very different (**Example 2**). Aggregated indicators
192 reflect the average ecosystem condition, where areas in very good or very poor condition have limited ability
193 to compensate for opposite extreme values elsewhere. The spatially aggregated variable on the other hand,
194 may reflect something like a sum of individuals, an average of a population, or some other aspect where
195 values above and below the reference levels are able to compensate for each other. The information held
196 by the indicator is also different from that of the variable since additional ecological knowledge can be
197 introduced via the reference levels.

198 In the statistical standard and recommended guidelines for ecosystem accounts ([United Nations, 2024;](#)
199 [2022](#)), there is no mention of aggregation displacement, and there seems to be little awareness in general of
200 its meaning and the ramification of choosing different spatial aggregation pathways for variables. Indicators
201 and variables are sometimes presented side-by-side in ecosystem condition assessments or accounts. This is
202 also recommended practice following the SEEA EA ([United Nations, 2024](#), ch. 5.3.4).

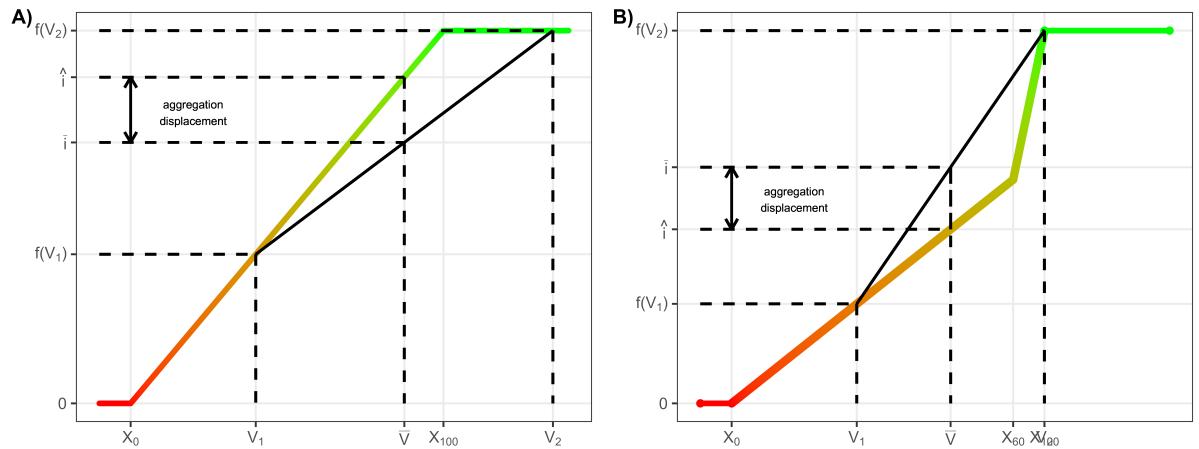


Figure 2: Examples showing the difference in indicator values (y-axis) obtained from taking the mean of two variable values V_1 and $V_1 (\bar{V})$ that are on the original scale (\hat{i}) or on the normalised indicator scale (\bar{i}). Pane A: Due to truncation at X_{100} , the latter results in a comparatively lower indicator value. Pane B: Example where the normalisation function includes a transformation step (see Figure 1 for definition) that anchors X_{60} to 0.6 on the indicator scale. This reverses the order of \hat{i} and \bar{i} compared to example in pane A. The solid coloured line represents the normalisation function $f(V)$. V = variable value, i = indicator value. Modified from Rastetter (1991).

Example 2 – Wolves

This hypothetical example (Table 3) shows how different the interpretation of a variable and an indicator can become when the information is spatially aggregated. More specifically, it shows how spatial compensation in the spatial aggregation of variables leads to aggregation displacement and a discrepancy between the variable and the indicator.

Variable: Number of wolves.

Reference levels: X_{100} = Number of wolves equal to what experts think the ecosystem would support under the reference condition. This number is informed by data on habitat quality, food supply, and more. X_0 = no wolves.

Table 3: Dummy data for the wolves example. EA = ecosystem asset (e.g. a municipality). EAA = ecosystem accounting area (e.g. country)

	EA 1	EA 2	EA 3	EAA aggregate
Variable values	20	5.0	0	Sum = 25.0
X_{100}	10	10.0	5	Sum = 25.0
Indicator values	1	0.5	0	Mean = 0.5

When species-based indicators are aggregated to the EAA level, it is common for the general public to interpret this value (0.5) as the status for this species, for example the conservation status. However, for the EAA seen overall, the population size is actually equal to the expected population size in the reference condition. Instead, the spatially aggregated indicator value describes the ecosystem condition for the different *areas* in terms of wolf under-abundance. Then we see that the first ecosystem asset has more wolves than we would expect under the reference condition, whereas the other two have less. Because variable values above X_{100} are truncated, the high wolf numbers in ecosystem asset one does not compensate for the low indicator value in assets two and three, and hence the mean indicator value is less than the sum of the variable values divided by the sum of the X_{100} values. But the high wolf numbers in asset 1 *does compensate* when looking at the aggregated variable value.

203
204 As we have seen, aggregation displacement causes a divergence in the type of information made available
205 through the spatial aggregation of variables versus indicators. In addition, unavoidable aggregation displacement
206 (for good and bad) will also affect the indicator values and the inferences that can be drawn from these.
207 A major determinant of the resulting aggregation displacement from the spatial aggregation of ecosystem
208 condition indicators (Figure 2) is the choice about the order of the different steps in the normalisation and
209 aggregation process, i.e. the aggregation pathway (Table 4). If normalisation occurs early in the aggregation
210 process, the amount of spatial compensation is limited (**Example 2**). However, sometimes complete or
211 partial compensation is justified (**Example 1** and **3**).

Example 3 – Water Framework Directive, indicator ASPT

Variable: ASPT (*average score per taxon*) is the mean eutrophication tolerance score of invertebrate species present in a river water body.

Reference levels: X_{100} = median variable value recorded in reference water bodies. X_{80} = lower boundary of variable values in reference water bodies. X_0 = natural zero (no species present). X_{20} ,

212

X_{40} , and X_{60} = intercalibrated threshold values, based on dose-response curves.

The Water Framework Directive (WFD) indicators use aggregation pathway 5 (Table 4), with truncation, scaling, and transformation, in that order. The value obtained after the first two steps is called an EQR (ecological quality ratio), and the value obtained after the third step is called nEQR [normalised EQR, and true indicator values *sensu* SEEA EA; [Van De Bund and Solimini \(2007\)](#)]. Spatial aggregation, the way that we use the term here, is not done for the WFD. Instead, the aggregated reporting metric is the proportion of water bodies in each of the five condition classes (“bad”, “poor”, “moderate”, “good”, “high”), separated by the non-terminal reference levels.

When WFD data is put into use in other contexts, however, aggregation becomes important, and it is crucial that aggregation is done after the (scaling and) transformation step, because the transformation (using a stepwise-linear function) adds ecological meaning to the data. As the example in Figure 3 shows, the ecologically meaningful interpretation is that the EAA has “poor” condition at time 1, improving to “moderate” condition at time 2. When aggregation is erroneously done before transformation, however, the same measurements suggest that condition is “bad” and deteriorating. This illustrates that an ecosystem condition indicator account cannot be derived directly from an ecosystem condition variable account in conjunction with reference levels, as suggested by SEEA EA ([United Nations \(2024\)](#): 5.76 and table 5.3). The reason in the case of ASPT is that the transformation function is non-linear, and aggregation displacement therefore occurs in the spatial aggregation of variables and indicators. Reference levels are the same throughout the entire EAA, and variation in reference levels is thus not part of the problem here.

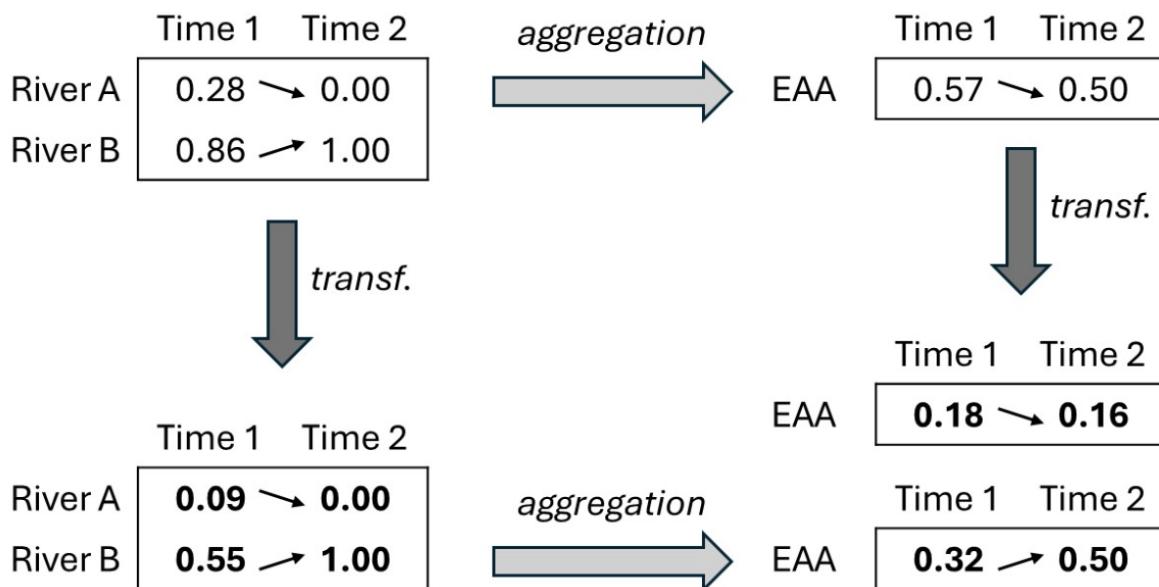


Figure 3: Different aggregation pathways can result in different indicator values, exemplified by the ASPT indicator from the WFD. Two ecosystem assets (Rivers A and B) are measured at two points in time. Regular font numbers are EQR values; boldface numbers are nEQR values (indicator values *sensu* SEEA EA). When EQR values are first aggregated and then transformed (“transf.”), ASPT incorrectly indicates a deteriorating and “bad” condition. When EQR values are first transformed and then aggregated, ASPT correctly indicates an improvement from “poor” to “moderate” condition.

Another issue that can be illustrated with ASPT (or other WFD indicators) is the effect of truncation. Aggregation pathway 5 uses truncation as the first step. When WFD data is used in ecosystem

condition accounting, however, truncation needs to be the final step, applied only after aggregation. This is because X_{100} is defined as the median of variable values measured in reference water bodies. In other words, half of the values measured in reference water bodies is expected to be above X_{100} . When truncation is done as the first step, the average indicator value of reference water bodies will be around 0.95, i.e. it would be prevented from actually reaching 1.0. Overshooting values therefore need to be preserved until after aggregation (spatial compensation), and only after aggregation should overshooting values be truncated to 1.0.

Likewise, in the case where model-based extrapolation of a WFD indicator is used, it is important to postpone truncation until after the modelling and extrapolation. Otherwise the distribution of the extrapolated values may be severely distorted, at least if many of the original measurements are in or close to the X_{100} value.

214

215 6. Aggregation pathways

216 We introduce the term aggregation pathway to describe the order of the steps used to go from a variable at
217 the measurement scale, to a spatially aggregated metric, usually an indicator, that describes the ecosystem
218 condition for a larger area. In Table 4 we show some aggregation pathways that we have come across,
219 and some that we see as potential new pathways. The examples are non-exhaustive, and serve mainly as
220 illustrations. We go on to describe how the aggregation pathways can formally, and succinctly, be described
221 using the names of these operations. The choice about which pathway to use is not trivial, and we want to
222 highlight some of the issues that could arise from having an *ad hoc* approach to these considerations.

223 Pathway 1 involves early normalisation using the perhaps most common order of the three steps: scaling,
224 truncating and transforming. The three steps may be done simultaneously or in sequence. Finally, the
225 indicator is spatially aggregated.

226 Pathway 2 involves aggregating the variable before normalising. This preserves the ability for very high or
227 very low variable values to compensate for very low or very high values elsewhere, respectively.

228 Pathway 3 is similar to pathway 2, but here there are two aggregation steps: one before and one after
229 normalisation. This can for example be the case when variables are aggregated to the scale corresponding
230 to the reference levels before they can be normalised (**Example 1**).

231 Pathway 4 illustrates the aggregation of a variable, with no normalisation. This is the pathway commonly
232 used for variable accounts in the SEE EA. For this, and all other aggregation pathways, the picture can be
233 made more complicated by adding additional aggregation levels (i.e. a step-wise aggregation).

234 Pathway 5 is a common pathway in the WFD, which does not practice spatial aggregation of indicator
235 values. Instead one reports the number of water bodies in each condition class (spatial statistics). Pathway
236 6 is a suggested pathway for handling WFD indicator in ECAs (see **Example 3**), where truncation is
237 postponed until after the spatial aggregation in order to allow overshooting values to compensate for low
238 indicator values elsewhere (what we refer to as compensation).

239 Pathway 7 describes an alternative to pathway 1 for a model-assisted aggregation pathway, where the
240 original sample is the result of a defined sampling strategy, but where a model is used to project (extrapolate
241 or interpolate, depending on the case) values to other spatial points or locations that were not sampled. The
242 resulting map (field of values) is then normalised, (re)sampled (which could imply taking all the discrete
243 population units (e.g. all rivers), and finally aggregated.

244 Pathways 8 and 9 describe alternative ways to create indices at different spatial scales, either by performing
245 the spatial aggregation on the indices (i.e. after thematic aggregation; pathway 8) or on the indicators
246 (i.e. before thematic aggregation; pathway 9). If all indicators making up an index are spatially aggregated
247 using the same weights, typically the extent of the spatial units, then the aggregation operations will be

248 commutative and it will not matter if you aggregate vertically then horizontally, or the other way around
249 (Table 4; Pathway 8 and 9, respectively). However, indicators are not always valid for the entire ecosystem
250 type that the account is made over. They can, for example, retain to only certain habitats or nature types
251 within the ecosystem type, in which case one might want to use different weights when spatially aggregating
252 the indicator that reflect the extent of only the relevant habitat or nature types, and not of the entire
253 ecosystem. This can be achieved using pathway 9.

254 7. Recommendations

255 Based on the above discussion and examples, we here summarise five recommendations for developers of
256 ecosystem condition indicators and assessments for avoiding some of the pitfalls from having a too casual
257 approach to the choice of aggregation pathways.

258 1. Report the aggregation pathway, using standardised terminology

259 ECAs should be accompanied by detailed indicator documentation where a precise description of the
260 steps in the aggregation process is presented. Verbose descriptions can be supplemented or replaced by a
261 standardised short-hand notation that we present in the following: We suggest using the terms as described
262 in Figure 1 and elsewhere in the paper: scale, truncate (abbreviated to *trunc.*), transform (*trans.*), spatial
263 aggregation (*sp. agg.*), thematic aggregation (*th. agg.*) and spatial statistics (*sp. stat.*). These terms can be
264 abbreviated as shown in the parentheses, and placed together into a single string, where operations performed
265 simultaneously are enclosed in square brackets. For example, pathway 1 in Table 4 can be annotated as
266 *scale – trunc. – trans. – sp.agg.*. If the three normalisation steps are performed simultaneously this can
267 be written as *[scale – trunc. – trans.] – sp.agg.*. If there are more aggregation steps, then the spatial level
268 at each step should be included in the description, e.g. for pathway 3: *sp.agg.(municipalities) – scale –*
269 *sp.agg.(country)*. “Municipality” and “country” could here be included as footnotes. Note also that in
270 the last example, normalisation only involved a scaling step. The description of indicator pathways can be
271 made even easier by referencing specific aggregation pathways by number, as we have done in this paper
272 using Table 4 in this paper. Methods used to change either the cover or the extent of the indicator data
273 (see Table 1) can also be included in the shorthand notation scheme. The three operations we conceive
274 as possible options are extrapolation (*extr.*), interpolation (*inter.*), and (*sub)sampling*. We use the term
275 spatial projection (projection for short) to encompass both extra- and interpolation. Thus, pathway 7 in
276 Table 4 can be written as *project – scale – sample – sp.agg. – trunc.* The type of model used for the spatial
277 projection can be added as a footnote.

278 Besides making the indicator workflow itself more transparent and reproducible, we believe this recom-
279 mendation would help raise the general awareness about aggregation displacement in ecosystem accounting,
280 both among users and developers. It will make the interpretation of ECAs less prone to misunderstanding
281 and misuse, as well as making troubleshooting easier, for example when trying to identify the reason why
282 two ECAs produce dissimilar indicator values from the same underlying data.

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

284 Normalising variables early in the aggregation pathway means that you are aggregating normative measures
285 of condition, which is generally what you want in ECAs (Section 2). But just like variables and indicators,
286 reference levels also have a spatial resolution, and they should only be used to normalise variables that are
287 at a scale which is relevant to the way the reference levels are defined, i.e. they are at a commensurable scale
288 (**Example 1**).

289 3. Use a similar aggregation approach for all indicators in the same assessment

290 It may be premature, or not even possible, to prescribe an aggregation pathway to be used for all ECAs, or
291 even a type of aggregation pathway to be used given the data at hand. However, internal consistency within
292 assessments should be possible, and this can make it easier to communicate and interpret the information
293 conveyed through the indicator values. This can be achieved by for example always scaling early (see

Table 4: Table showing a selection of nine possible 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 SSEA EA, which may include some, but not necessarily all, of the steps scale, truncate and transform. The pathway description uses the standardised shorthand aggregation pathway terminology, where trunc. = truncation, trans. = transformation, sp. agg. = spatial aggregation, proj. = project (extrapolation or interpolation), sample = sub-sampling from a larger dataset, th. agg. = thematic aggregation.

Number	Pathway graphic	Pathway description
1	<pre> graph LR scale[] --> truncate[] truncate --> transform[] transform --> agg1[spatial aggregation] normalise1[normalise] --> transform </pre>	[scale – trunc. – trans.] – sp. agg.
2	<pre> graph LR agg2[spatial aggregation] --> normalise2[normalise] </pre>	sp. agg. – [scale – trunc. – trans.]
3	<pre> graph LR agg3[spatial aggregation] --> normalise3[normalise] normalise3 --> agg3_2[spatial aggregation] </pre>	sp. agg. – [scale – trunc. – trans.] – sp. agg.
4	<pre> graph LR agg4[spatial aggregation] </pre>	sp. agg.
5	<pre> graph LR truncate[truncate] --> scale[] scale --> transform[] transform --> stats[spatial statistics] </pre>	trunc. - scale – trans. - sp. stat.
6	<pre> graph LR scale[] --> transform[] transform --> agg6[spatial aggregation] agg6 --> trunc6[truncate] </pre>	scale – trans. - sp. agg. – trunc.
7	<pre> graph LR project[project] --> normalise7[normalise] normalise7 --> sample[sample] sample --> agg7[spatial aggregation] </pre>	proj. – [scale – trunc. – trans.] – sample – sp. agg.
8	<pre> graph LR norm1[normalise] --> agg8[thematic aggregation] norm2[normalise] --> agg8 agg8 --> agg8_2[spatial aggregation] </pre>	[scale – trunc. – trans.] – th. agg. – sp. agg.
9	<pre> graph LR sub9_1[normalise] <--> sub9_2[normalise] sub9_1 --> agg9_1[thematic aggregation] sub9_2 --> agg9_2[spatial aggregation] agg9_2 --> agg9_3[thematic aggregation] </pre>	$[scale – trunc. – trans.] – th. agg.$ <p>OR</p> $[scale – trunc. – trans.] – sp. agg. – th. agg.$

294 recommendation number 2 above) and using the same aggregation levels (same spatial units) and same
295 approach to step-wise aggregation across levels, for all indicators.

296 *4. Use unique indicator IDs , also for indicators that are similar, but use different aggregation pathways*

297 Indicators (and variables) often exist in multiple versions, varying slightly in the raw data or in the methods
298 or aggregation pathway used to produce the data or the metrics. Yet different versions are often referred to
299 by the same common name, for example in nested or repeated ECAs. This causes confusion about which
300 indicator version is being used, and thus making it difficult to make out which aggregation pathway has
301 been used. We need to acknowledge that the aggregation pathway can affect the indicators (and indices) so
302 much that the use of different pathways imply that metrics are named and treated uniquely. We recommend
303 making use of stable and unique indicator IDs and version numbers. This has for example already been
304 implemented in ecRxiv, a GitHub-based publishing platform for ecosystem condition indicators used in the
305 Norwegian national pilot ECA ([Kolstad and Grainger, 2024](#)). On ecRxiv, indicator documentation follows
306 a structured approach to both reporting and peer review (including code review). Each indicator version
307 is given its own ID, and its own fact sheet with a persistent URL, so that ECAs that use these indicators
308 can unequivocally cite specific indicator versions, and how they looked at a given point in time. ecRxiv also
309 includes standardised metadata reporting schemes with fields for ecosystem type (IUCN GET; [Keith et al.](#)
310 ([2020](#))) and aggregation pathways (see recommendation number 1 above).

311 *7.0.1. 5. Don't aggregate indices, unless you know all aggregation operations are commutative*

312 When spatially aggregating indices it is no longer possible to use different area weights to each single
313 indicator.

314 When spatially aggregating indices (Table 4; pathway 8) you loose this ability to give different weights
315 to different indicators. The result can be that the aggregated index value will not be determinable from
316 the aggregated indices, and that ECAs using the same indicator set, but focusing on different spatial scales
317 (e.g. one one presneting regional values only, and another also presenting local values), will not get equal
318 index values for the same areas, even though they use the same indicator set. We therefore recommend
319 caution, and to default to the solution of instead of spatially aggregating indicators separately, and then
320 re-calculating indices when needed (Table 4; Pathway 9). This will ensure that nested accounts will be
321 comparable, i.e. that they will present the same index values independent of which spatial units the indices
322 first are calculated for.

323 *7.0.2. 6. Don't present variables and their respective indicators as alternative evidences to choose from*

324 Aggregation displacement causes a divergence in the type of information held in ecosystem condition
325 variables versus indicators, and spatially aggregated indicators should not be interpreted as normalised
326 versions of aggregated variables. Therefore, aggregated variables and the associated aggregated indicators
327 cannot act as alternative evidence or interpretations for the state of nature. While this may initially seem
328 like a democratic and transparent approach to reporting, this practice places a significant burden on both
329 the end user and the indicator developer. Misuse can ensue, for example by taking the variable value and
330 assigning it the same interpretation as the indicator value. At the very least, the developer must clarify to
331 the user how the two metrics may have diverged during spatial aggregation and normalisation, complicating
332 the comparison of their respective information. Generally, because of the normalisation process, indicators
333 are more aligned with the purpose of ECA with describing ecosystem condition in normative terms, than
334 variables. Although variable accounts are allowed under the SEEA EA framework, and are indeed a central
335 feature, we believe they should be seen as interim accounts for metrics that cannot be, or have not yet been,
336 normalised.

337 **8. Conclusion**

338 This paper has described the reasons why we need to do spatial generalisation in ecosystem accounting,
339 and clarified several misconceptions about this process. We have showed that indeitcal raw data, when

340 spatially aggregated through different pathways, can yield fundamentally different types of information
341 about ecosystems condition. The recommendations offered here is intended to help researchers design
342 ecosystem condition metrics that better align with the type of information they aim to communicate from
343 the data, while also improving transparency through the use of a standardised terminology. With a clearer
344 understanding of the challenges inherent to spatial generalisation, we hope future ecosystem condition
345 accounts will be more internally consistent, more comparable between each other, and less susceptible to
346 unintended mathematical artefacts.

347 9. CRedit statement

348 **Anders Kolstad:** Conceptualization, Data Curation, Writing - Original Draft, Visualization, Funding
349 acquisition. **Hanno Sandvik:** Conceptualization, Writing - Review & Editing, Visualization. **Bálint
350 Czúcz:** Conceptualization, Writing - Review & Editing. **Chloé R. Nater:** Conceptualization, Writing -
351 Review & Editing.

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