The role of local reference levels in assessing ecosystem capacity

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Questions to the London Group:

- How do you judge the potential of using condition variables and references to support the estimation of ecosystem service capacity?

- Are the proposed methods to obtain reference levels appropriate?

I. Introduction

Ecosystem condition accounts serve at least three main functions within ecosystem accounting. First, they describe "the quality of an ecosystem, measured in terms of its abiotic and biotic characteristics" (United Nations et al. 2021), thus providing a spatially explicit time-series of monitoring data that reflects the ecosystem's integrity. Second, condition accounts provide a direct link between ecosystem assets and the provision of services. Condition data is used to derive services, understand an ecosystem's ability to provide them or understand the human impact on ecosystems. Third, we argue in this paper that condition accounts can help to estimate sustainable paths of service flows (ecosystem capacity) by providing pairings of condition variables and appropriate reference levels as described in SEEA EA para. 5.65. In particular, if the relation between current service flows and future service potential[1] is unknown, non-linear or dynamic, condition indicators can support the estimation of capacity.

Condition accounts contain specific condition variables for different ecosystem types. These variables are selected based on several criteria, e.g. relevance, reactiveness to anthropogenic influence and measurability. Condition variables can be accompanied by reference levels that provide a baseline, scale orientation or normative interpretation. Defining appropriate reference conditions and values allows transforming variables into indicators. There are a number of methods to define these references, e.g. natural, pristine or historic states as well as expert-based references or best-attainable condition. Reference levels play a significant role in all major functions of condition accounts. They provide an anchor to interpret levels and changes in condition variables, and thus ecosystem integrity. Additionally, pairs of condition variables and reference levels may enhance the estimation of ecosystem capacity. Therefore, appropriate and local reference levels are a valuable feature of the condition account.

This short paper discusses the potential application of condition variables and references levels to estimate ecosystem capacity and describes the opportunities and challenges of identifying appropriate reference levels to do so. To motivate the inclusion of reference levels in ecosystem condition accounts, we first highlight how reference levels may support the estimation of ecosystem capacity and/or function as so-called capacity indicators. Then we present methods to identify ecosystem-specific reference conditions and calculate appropriate local reference levels that could be used to assess capacity.

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[1] We use the term ecosystem service potential as the maximum possible supply of an ecosystem service.

Ultimately, the objective is to prepare ecosystem condition accounts for a wide range of potential use cases and capture all the necessary information to support sustainable policies. Ecosystem capacity is one such use case. The potential of calculating ecosystem capacity lies in the sustainable use of ecosystem services, the possibility to prevent harm on the ecosystems at an early stage. Further, it can provide policy advice to ensure that ecosystems and their services can be enjoyed by future generations.

Estimating ecosystem capacity is complex, because it requires a combination of extent, condition and services accounts. There have been different concepts of capacity in the past, though most share a common concept or definition (Villamagna et al. 2013). For instance, Burkhard et al. (2012) states capacity as the long-term potential supply of ecosystems services. SEEA EA includes a consolidated definition of ecosystem capacity: "The ability of an ecosystem to generate an ecosystem service under current ecosystem condition, management and uses, at the highest yield or use level that does not negatively affect the future supply of the same or other ecosystem services from that ecosystem" (United Nations et al. 2021). Nevertheless, the framework still lacks technical guidance to estimate ecosystem capacity at different levels of complexity, e.g. multiple services and/or multiple ecosystems.

II. Adding Condition Indicators to Ecosystem Capacity

Ecosystem services flows are the actual, realized flows of services from ecosystems to users, while capacity is defined as "the long-term potential of ecosystems to provide services […] in a sustainable way" (Schröter et al. 2014). Theoretically, capacity is a function of current and future ecosystem condition, extent and management, although in previous applications these factors have been held constant at current levels (e.g. Hein et al. 2016, La Notte et al. 2019). The crucial challenge is to define and identify a sustainability threshold for each service. Sustainability is typically defined as a stable future provision of the service (Hein et al. 2016), but in a general framework, it could also be defined as stable condition (integrity) or extent (no collapse).

The capacity for a specific ecosystem service (ES) *i* in period *t* can be described as a total stream of sustainable service flows (ES^{sust}) provided by ecosystems *1…n* (Obst & Edens 2019).[2]

$$Capacity(ES_i) = \sum_{j=1}^{n} ES_j^{sust}$$

A sustainable ecosystem flow (ES^{sust}) of an ecosystem asset is defined as the maximum ecosystem flow, which ensures that future ecosystem potential remains stable. Thus, sustainability is implicit in the evolution of ecosystems' potential to provide service. For simplicity, this ecosystem potential (EP) for the next period can be conceived as a function of current service flow ES (how much of the potential is used) and external shocks or influences (e.g. climatic or weather shocks, external trends in condition).

For a provisioning service like wood provision, setting the services flow equal to net increment in available timber would represent a unique optimum of the capacity problem. For other services the relation between potential and actual flow is unknown (e.g. recreational services). For regulating services, this issue is often addressed by setting the capacity equal to the actual service flow. However, excessive use of regulating services may negatively affect future potential through degradation. One may also wish to include resilience to external shocks and influences in the definition of sustainable

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[2] Variations of this approach can be represent the capacity of a single ecosystem asset by summing up sustainable flows from multiples service or expand to a full system of equations across all ecosystem services and assets.

services flows (for instance, because shocks are likely to be correlated). Furthermore, extending the concept of capacity to multiple (competing) services increases the complexity of the system exponentially.

It may therefore be a useful remedy to use additional condition indicators as intermediaries, when determining ES^{sust}. There are two distinct ways condition indicators can provide support:

a. Use of condition indicators that are directly affected by the service as constraints when finding the maximum sustainable service flow. Condition indicators, a function of condition variables and appropriate reference levels, should remain above a given threshold or stay within a defined range. Therefore, capacity would be defined as the actual service flow that satisfies this constraint over time.
b. Use of condition indicators not directly affected by the service to adjust capacity to external ecological influences and shocks (e.g. use marine condition variables to determine the assessment of maximum sustainable yields for fisheries).

Integrating condition indicator into existing approaches to determine capacity has several potential advantages:

1) A more holistic, less anthropogenic perspective: Requiring stability in a large set of condition characteristics is a stronger overall constraint, less focused on short-term service provision. Sustainability defined this way may result in a better resilience to external shocks and may therefore improve long-term stability in service provision.
2) Estimating capacity for multiple (competing) services simultaneously is facilitated. The relation of services to condition characteristics is potentially better understood than the relation of current services to future services. Condition constraints can help to select between multiple capacity equilibria.
3) The system can be extended to include management choices. While this is also true for service-focused sustainability concepts, condition accounts provide a structure for the causal link between management, condition and services.
4) Analysis of capacity can potentially be extended to services for which the relation between current and future service potential is not straightforward (e.g. recreational services).

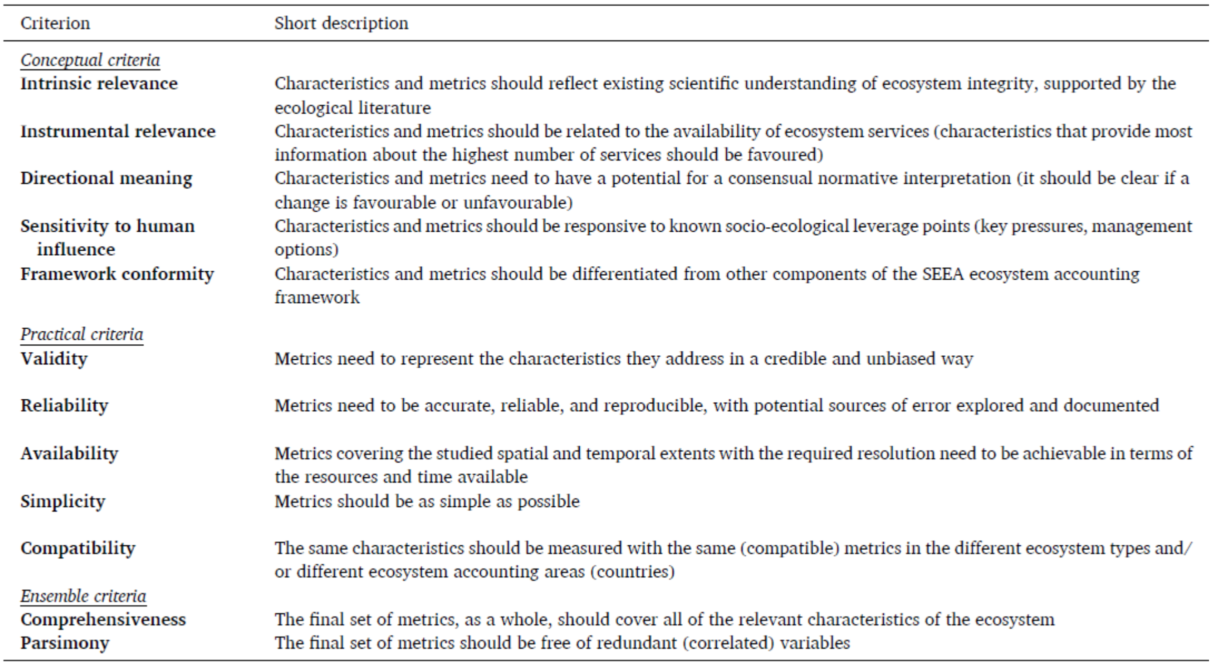
Challenges that limit the application of condition indicators for capacity are:

1) Challenge to identify a sufficient set of condition indicators to reflect all necessary characteristics to define sustainable flows.
2) Difficulty to collect condition data at necessary temporal and spatial resolution.
3) Difficulty to identify relevant reference levels at necessary temporal and spatial resolution.

III. Condition Variables and Local Reference Levels

There are several requirements on the choice of condition variables, reference conditions and the specification of reference levels, that condition account should met in order to inform on the sustainable use of ecosystem services (and thus to calculate capacity).

First, the condition account should be a structured representation of different characteristics (abiotic, biotic, landscape) for each ecosystem. SEEA EA proposes a general ecosystem condition typology (ECT) to arrange variables and data. It avoids double counting and reflects the condition of each ecosystem in a comprehensive approach (United Nations 2021, Table 5.1). The second requirement lies in the quality of data. To get satisfactory results, the data has to encompass certain criteria: conceptual, practical and ensemble criteria (see Table 1). The third requirement lays in the choice of adequate methods to select appropriate reference levels, or find new ones, if necessary.



Criterion	Short description
Conceptual criteria	
Intrinsic relevance	Characteristics and metrics should reflect existing scientific understanding of ecosystem integrity, supported by the ecological literature
Instrumental relevance	Characteristics and metrics should be related to the availability of ecosystem services (characteristics that provide most information about the highest number of services should be favoured)
Directional meaning	Characteristics and metrics need to have a potential for a consensual normative interpretation (it should be clear if a change is favourable or unfavourable)
Sensitivity to human influence	Characteristics and metrics should be responsive to known socio-ecological leverage points (key pressures, management options)
Framework conformity	Characteristics and metrics should be differentiated from other components of the SEEA ecosystem accounting framework
Practical criteria	
Validity	Metrics need to represent the characteristics they address in a credible and unbiased way
Reliability	Metrics need to be accurate, reliable, and reproducible, with potential sources of error explored and documented
Availability	Metrics covering the studied spatial and temporal extents with the required resolution need to be achievable in terms of the resources and time available
Simplicity	Metrics should be as simple as possible
Compatibility	The same characteristics should be measured with the same (compatible) metrics in the different ecosystem types and/ or different ecosystem accounting areas (countries)
Ensemble criteria	
Comprehensiveness	The final set of metrics, as a whole, should cover all of the relevant characteristics of the ecosystem
Parsimony	The final set of metrics should be free of redundant (correlated) variables

Table. 1: Selection criteria for ecosystem condition variables and their corresponding data (Czúcz et al. 2021 changed)

In addition to these general criteria, condition indicators should reflect a normative threshold or target range based on natural, natural-historic, expert-based or best-attainable condition in order to be suitable for the estimation of capacity.

Example 1: Forest ecosystems

For forest ecosystems, the German condition account will have local reference levels of the category “natural/pristine” for several condition variables. First, we need to define local contexts for forest ecosystems, i.e. identify areas that show similar ecological conditions and that represent appropriate spatial units for referencing. To do so, we use a map of forest growing districts *(Wuchsbezirke)* (Gauer J. & F. Kroiher 2011). This map differentiates growing areas by a number of relevant characteristics, e.g. climatic conditions, soil, historical development of the landscape and atmospheric influences. The map divides the terrestrial area of Germany into 608 different forest growing districts.

As in Germany only a few pristine forests remain, we identify forest patches that are as close to the natural state, i.e. are the least disturbed. First, forest patches in the extent account are intersected with nature protected areas. Since areas that have been protected only recently are not likely to meet the requirement of quasi-naturalness, only certain protected areas are considered. Protected areas must meet protection criteria (e.g. IUCN criteria II or higher) for a certain amount of time (e.g. 10 years). This step is necessary to balance the need to get a large enough sample size of protected forest patches for each growing district and the aim to include reference areas that are as pristine as possible.

The next step is to add values of the condition variable of interest, e.g. a raster dataset of NDVI, Tree Cover Density or pH-values. For each reference area (protected forest patches) the mean of the condition variable needs to be calculated via zonal statistics. To define a unique reference level for each growing district, these values are aggregated to each growing district using an area-weighted mean. Figure 1 shows the Area weighted pH-Values per growing district for broadleaf forests in Germany (Scherstjanoi et al. 2021). If there is a time series of data available, the mean out of all time steps per growing district will be taken. Ideally, the reference levels within a given growing district should be as homogenous as possible, since this would suggest that there is indeed a common reference level shared by pristine areas in the same local context. Therefore, we calculate the area-weighted mean standard deviation of reference levels in all reference areas for each growing district.

If the mean standard deviation of a growing district is low, this growing district delineates the local reference context well. If the standard deviation is high, we proceed as follows: First, we check whether the heterogeneity in reference levels within this growing district is a common feature in the wider landscape around or whether it only affects one growing district. In case of the latter, one option is to increase the reference area sample and eliminate outliers by setting a buffer around the reference areas. Ultimately, it depends on the condition variable at hand, what level of homogeneity in reference levels is required to use growing districts as local spatial contexts.

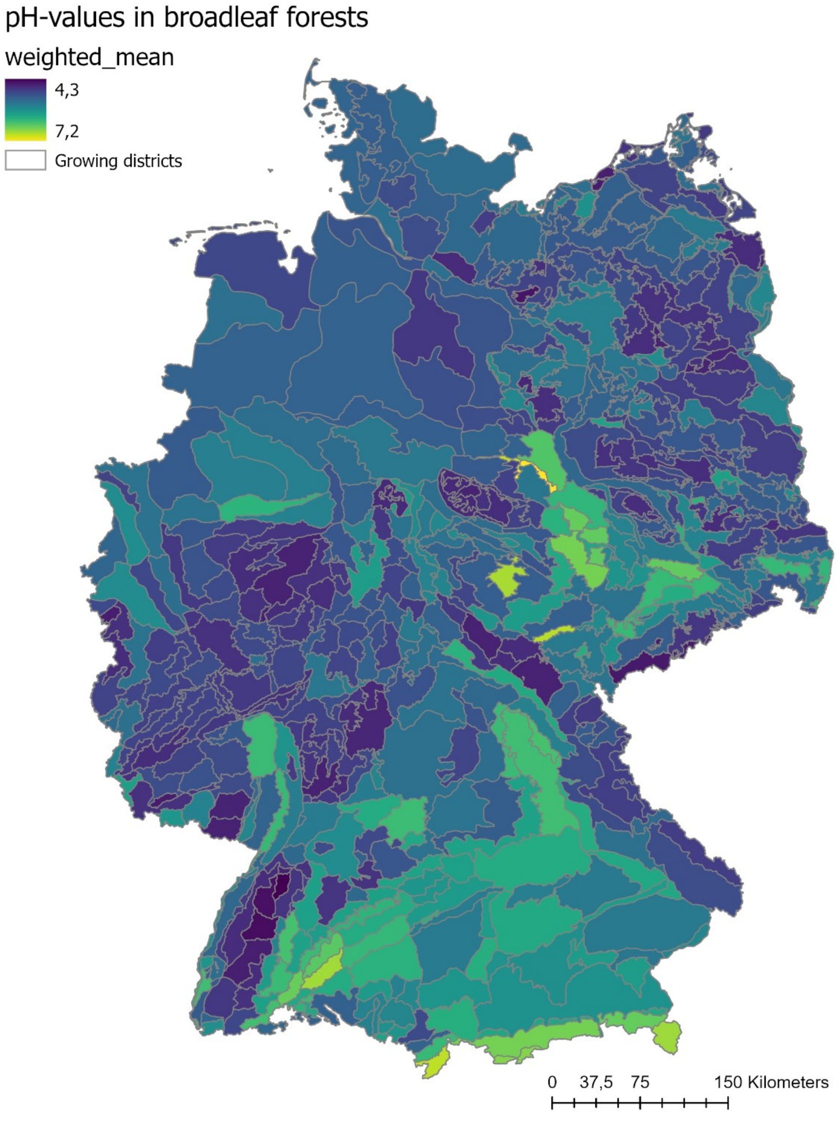


Figure 1: Area weighted pH-Values per growing district for broadleaf forests in Germany

The result of this procedure is a local reference level for every growing district with common climate, soil and other ecological condition. It is also possible to use a local reference in line with lower and upper reference levels suggest in SEEA EA, e.g. the 25th and 75th percentile. Finally, even if applied consistently, this reference method should be validated using scientific literature or expert knowledge.

Example 2: Marine Ecosystems

For marine ecosystems, we can rely on existing regulatory references for some of the condition variables. For instance, within European Marine Strategy Framework Directive (MSFD), the Helsinki Commission (HELCOM) and Oslo-Paris Commission (OSPAR) member states jointly set target values for Eutrophication. Specifically, for variables capturing the direct effects of eutrophication, different thresholds for total nitrogen, total phosphor and chlorophyll-a are set at the level of marine areas, see Figure 2. These thresholds are based on statistical analyses of eutrophication time-series:

> *"The statistical trend analyses […] suggest […] a three-phase development from an early pre-eutrophication phase before ca. 1940; a eutrophication phase between 1940 and 1980; and a eutrophication stagnation phase after 1980, i.e. suggesting that the organic loading of the system has stabilised." (HELCOM 2013)*

Thresholds in the German Bight and the Baltic Sea are set locally and adjusted to salinity, but with the overall objective to not deviate significantly (depending on the area up to 50%) from the levels at the end of the eutrophication phase. Figure 2 shows reference levels for total nitrogen concentrations in $\mu M/l$. Note that these thresholds are subject to change with new iteration of MSFD reporting cycles. For some marine areas in the Baltic Sea, countries member states of HELCOM have not agreed on thresholds (yet).

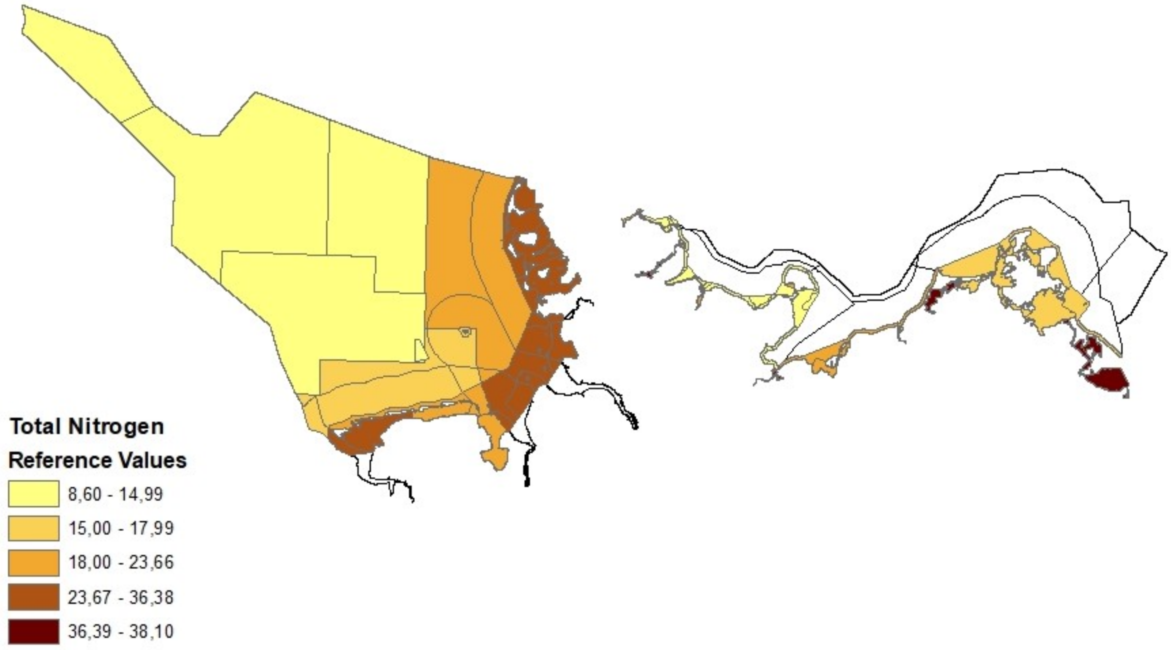


Figure 2: Reference values for total nitrogen from MFSD thresholds set by HELCOM and OSPAR

Example 3: Agricultural Ecosystems

To define appropriate local reference levels for variables in agricultural ecosystems, the reference level concept of best-attainable is used. Three additional datasets are necessary.

First, the soil climatic regions (SCR) map divides Germany into 58 regions, based on certain soil and climate variables (see Figure 3) (Roßberg et al. 2007). Second, the soil quality rating (SQR) assesses the suitability of soils for agricultural use and estimates the yield potential. Input data for the SQR are, inter alia, the soil overview map, produced by the Federal Institute for Geosciences and Natural Resources (BGR), climate data provided by the German weather service (DWD) and information on landcover by Corine. The SQR-score ranges from 0 to 100 and can be classified into "Very poor" (SQ: < 20), "Poor" (SQ: 20 – 40), "Moderate" (SQ: 40 – 60), "Good" (SQ: 60 – 80) and "Very good" (SQ: > 80) (Mueller et al. 2007). Finally, the map of main crop types by the Thünen-Institute uses combined time series of Sentinel-1, Sentinel-2 and Landsat 8 data for Germany and can detect up to 23 crop types (Blickensdörfer et al. 2022).

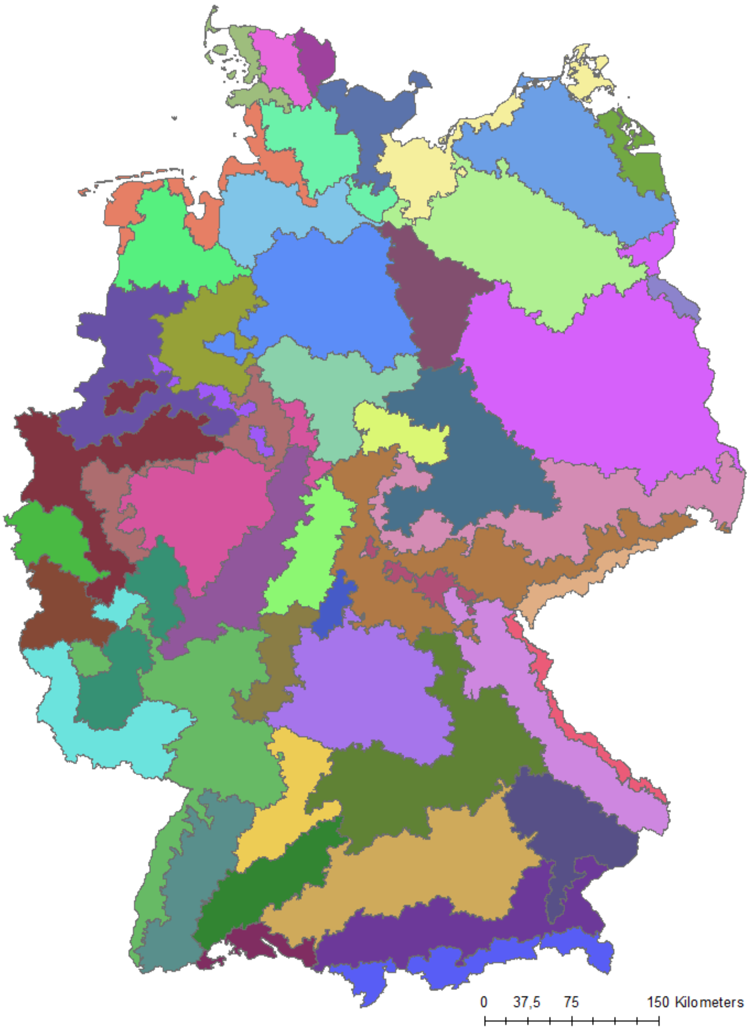


Figure 3: Soil climatic regions in Germany

The approach compares land parcels with a similar agricultural yield potential in each soil climatic region. In case of annual agricultural land use, only the same crop types will be compared with each other. Using the 90th percentile of the relevant variable, e.g. productivity (NDVI), omits possible outliers and enables a relevant comparison of a land parcel to its local reference level. Low values in comparison to the reference therefore indicate lower productivity and a worse condition than expected. With this approach, it is possible to compare the best attainable values for each class in a soil climatic region. Likewise, to the approach for local reference levels in forest ecosystems, this method needs proof of confidence. Calculating and comparing standard deviations and area ratio between reference areas and SCR are required.

IV. Conclusion

Capacity, defined as the sustainable use of ecosystem services, is a crucial concept for environmental policy and conservation efforts. The SEEA EA framework broadly defines it, but gives no technical guidance to calculate it and on the data needed to do so (United Nations et al. 2021). We suggest that even under the standard definition, information from all three accounts (extent, condition, services) can be used to estimate capacity. In fact, combining condition indicators and service potential may allow for a more holistic view on sustainable service use.

We propose that if "Ecosystem capacity indicators should be able to spatially reflect changes in ecosystem condition in space and time, and the implications in the future ecosystem services supply" (Vargas et al. 2019), a combination of constraints regarding condition indicator and service potential can be used to define the maximum sustainable service flow.

For instance, in case of fish provisioning service, catch rates are announced regularly. These catch rates equal capacity of this service, when defined by a constraint of stable future potential. However, it is possible that there are other environmental effects, monitored in the condition account. Suppose one condition indicator is displaying the eutrophication of the water. A slight increase might be still in the range of our reference condition values, but the trend can be significant. In this case, it may be advisable to regulate the catch rate according to the trend at an early stage.

Ideally, condition variables and reference levels are relevant, local and measured at appropriate spatial and temporal resolution. Vargas et al. (2019) show that ecosystem capacity differs by location, giving further motivation to a local approach. By using local reference levels, support for the calculation of capacity for future services are more precise. We suggest that for some ecosystem types and characteristics, local reference levels that can inform on capacity are already available, while in others they can be constructed using relatively simple steps.

A robust estimation of capacity requires longer time series for extent, condition and services than currently available. However, now that the regular production of national ecosystem accounts is initiated in many countries, it is worth considering the data requirements for such uses in the future. Capacity touches on crucial concepts of the condition account, such as integrity, stability and resilience, and any effort to collect adequate condition data to analyze capacity will likely improve the quality of the account overall.

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