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SAMMENDRAG/SUMMARY:

Denne rapporten beskriver utviklingen av en ny metode og en digital kartløsning for å visualisere ulike økosystemtjenester på nasjonal skala i Norge.

This report describes the development of a novel model & digital map system for visualising diverse ecosystem services at national scale in Norway.

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Abstract

This report presents a model for assessing land according to the ecosystem services (ESS) that it provides. Areas of land may support or relate to a variety of distinct ESS in complex ways and the ideas of 'value' and 'service' and how to represent them quantitatively are not agreed upon. Our model overcomes this complexity and lack of consensus by using a very large number of simple functions, arranged hierarchically in a manner that allows both cooperation and competition between alternative sub-models and varying source datasets. This allows an approximate but useful overall characterisation of the ESS associated with an area, wherever data is available to support it, without requiring complete map coverages, and without requiring consensus among researchers on the issues of source data or service modelling.

Our aim is to provide an easy to use tool as an aid in land use planning and policy making. Our approach addresses a variety of qualitative and quantitative challenges in land assessment: capturing the beliefs and judgements of researchers, decision makers, interest groups and the general public; representing individual, group and national concepts of value; selecting numbers to represent abstract ideas; providing a democratic system for building consensus about the meaning of land data while leaving freedom to explore new theories; and separating subjective and objective aspects of assessment of land data.

We cannot guarantee that this tool is without errors, or take responsibility for how it is used by others. However, both the theoretical model and the technical approach are designed to enable other research groups to re-use our data, branch the work in new directions, explore alternative ideas and ESS models, and re-integrate results together again.

This report was written by Graeme Bell, Wenche Dramstad, Christian Pedersen, Lars Aksel Opsahl and Wendy Fjellstad.

Ås, 07.08.19

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1 Introduction

1.1 The need to map ecosystem services

The EU 2020 Biodiversity Strategy Action 5 requires Member States, with the assistance of the Commission, to "...map and assess the state of ecosystems and their services in their national territory by 2014, assess the economic value of such services, and promote the integration of these values into accounting and reporting systems at EU and national level by 2020" (Maes et al. 2013). Norway, although not a member of the EU, is following a similar path. An Official Norwegian Report (NOU[1]) was published in 2013 (NOU 2013:10) focusing on the current state and trends of development in Norwegian ecosystems. The report points to the need to map ecosystem services (ESS) to enable knowledge based management, but also documents a severe lack of knowledge affecting a variety of themes. This is cause for concern, since the pressures on ESS worldwide are likely to continue increasing (Rodriguez et al. 2006, Seto et al. 2011).

For informed decision-making, for research, for education, and even for increasing people's recreational and aesthetic enjoyment of the environment, we need to understand and visualize ESS in a broad sense over wide geographical areas, i.e. develop "understanding of the landscape/ecosystem service connection" in the words of Andersson et al. (2015). Only when we have this structured and systematic overview will we be able to evaluate trade-offs and synergies between different geographic areas of interest, with the overall aim of better informed choices in decision-making, landscape management and planning (Raudsepp-Hearne et al. 2010, Naidoo et al. 2008). Currently, many trade-offs between different ESS go unrecognised, or are accepted due to lack of knowledge or understanding or even systematic misrepresentations (Rodriguez et al. 2006, Hauck et al. 2013). Yet trade-offs can sometimes be avoided (Raudsepp-Hearne et al. 2010). To move forward, better maps are needed (Naidoo et al., 2008) - and thus better approaches to map construction are needed.

1.2 The state of the art

There have been many research efforts that have mapped ESS (Maes et al. 2012; Naidoo et al. 2008, Raudsepp-Hearne et al. 2010, Maes et al. 2016; Martínez-Harms et al. 2016). The number of ESS and the specific details of the ESS that are included varies, as does the temporal scale and resolution, spatial scale and resolution, and GIS representation (data type and projection). Data availability often constrains what can be mapped (Naidoo et al. 2008). Models have tended to focus on either a limited number of themes (such as cultural heritage or biodiversity) - particularly those specific to a current project - or have focused on a particular local/regional geographical area.

Outside of academic ecosystems research, however, public land use plans must accommodate a wider range of interests: housing, infrastructure, trade and industry, agriculture, recreation, etc. Those making such plans are unlikely to be paying special attention to ecology (Ahern 2005, Thompson 2002). Indeed, Thompson (2002) found that landscape architects were more willing to give way on matters of ecology than on matters of design aesthetics. Landscape planners also face an "imperativeto act" (Ahern 2005) and there is often insufficient time and funding available to conduct the thoroughinvestigations desirable from an ecological perspective in all potential locations. This makes it all the more important to systematically collect, organise and effectively aggregate existing information on ecosystems *a priori* – before a direct and immediate need for such information arises - into a single decision support system that presents ecology and ESS data in a comprehensive, comprehensible and easily accessible manner.

Digital maps are already indispensable instruments in planning as well as a functional communication tool in research (Hauck et al. 2013), and thus they are a logical platform for systematic documentation of ESS. In this report we outline a digital map model that captures and presents "the big picture" while preserving the ability to inspect fine details, and which can readily accommodate further themes and details as new data sources & interpretations of data become available.

1.3 What should be mapped, and how?

The concept of ESS is anthropocentric. Only what is valued, needed or required by humans can be called an ESS (Jax 2010). These values, needs and requirements are variable in time, location and between different groups of people. If there are no users of the provided service, it does not fall under the definition of service, although it holds potential (Bastian et al. 2012).

Some benefits to humans are derived from complex interactions of ecosystem structures, processes and intermediate services, combined with other forms of capital (Fisher et al. 2009). For example, the benefits of recreational cycling are dependent on a bike and possibly built cycle tracks, in addition to various ecological components.

Land cover and land use explain a considerable part of the variation in the spatial supply of ESS in Europe (Maes et al. 2012), e.g. wood for timber, agricultural land for food. Other services may be modelled using additional data, such as landscape data based on expert knowledge, literature reviews or process models (Hermann et al. 2015, Fernandez-Campo et al. 2017).

Scale is also important. ESS may be generated and supplied only at certain spatial or temporal scales. Some services are relevant at more than one scale, and pressures on ecosystems can have effects at different scales (Hermann et al. 2011). Map units used should be “ecologically reasonable and policy relevant” (Bastian et al. 2015). One approach is to define Service Providing Units (SPU, Luck et al. 2003, Andersson et al. 2015), mappable units that possess qualities that enable the provision of a service. SPU may be variable in extent, based on the service in question (sensu Andersson et al. 2015). An SPU for forestry may be an entire forest, whilst an SPU for aesthetic appreciation may be a solitary tree in a field or an urban square.

The approach of this report allows the cooperative use of datasets and data interpretations that are defined at varying scales/resolution (i.e. the overall model is not tied to a single SPU), by tracking all inputs and interpretations in fine detail simultaneously at national scale. Interpretations and results are derived in parallel, aggregated hierarchically and cached, in order to enable high performance inspection and visualisation of increasingly broad ‘big pictures’, offered at multiple spatial scales.

1.4 The concept of ‘value’ for ecosystem services

Ecosystems can be more or less objectively defined and mapped. However, the values (economic, social, cultural, intellectual…) associated with different ESS have been shown to be stakeholder, time and location dependent (Hauck et al. 2013, Schröter et al., 2005; Palacios-Agundez et al. 2014; Andersson et al. 2015). For example, a woodland on the edge of a town might be heavily used for recreation, whilst an almost identical woodland some kilometres away might be seldom visited. The dog-walking population might value the wood closest to their home most, whilst the local orienteering club might value the lesser used woodland more. Even different academic disciplines may have different, and sometimes opposing, values.

In relation to this aspect of ESS, we therefore aimed to create a system that would allow different sets of values to be modelled, and represented within maps, inside the same system. This would enable better understanding of trade-offs and synergies between different sets of values (and approaches to valuing), better integration of knowledge across disciplines, and could contribute to making land valuation a more democratic process by enabling visualisation and inspection of the ways in which a multiplicity of viewpoints agree or are in conflict. In particular, by visualizing graphically where conflicts of values are likely, where trade-offs must be addressed and where data gaps exist, the system should raise awareness of each of these issues as well as more generally raising awareness of the multitude of aspects and values to be considered in land use plans.

We now document the development of an *ESS Tree* model and a software system that allows the integration of all forms of ESS within a single map-based and database-driven solution. As far as we are aware, there are no previous attempts to accommodate all forms of ESS, allowing multiple interpretations of each individual ESS, diverse underlying data sources, at national scale and with the capacity for both broad and detailed visualisation and inspection – all in a fully open access manner.

2 Methods

2.1 Choice of ecosystem services to include in the ESS Tree model

A starting point for our work was the Norwegian Official Report (NOU 2013:10) listing the ESS considered to be of particular importance under Norwegian conditions. The assessment builds on a review of the Millennium Ecosystem Assessment (MEA 2005), TEEB (TEEB 2010) and CICES (Haines-Young and Potschin 2013), as well as various national and European categorizations of ESS. The report categorises ESS according to the MEA categories of *cultural, provisioning, regulating* and *supporting*.

Our first step was to make a three level hierarchical model with all of the agreed ESS allocated to their main category (see Figure 1) and given a unique identifying code number. A group of experts in ecology, agriculture, soil sciences, cultural heritage, computer modelling and GIS were then engaged in a discussion about individual services within their field of expertise. For each service, the experts were asked what would contribute positively, negatively or neutrally to its provision, based on their assessment of evidence from the scientific literature where possible. We then identified existing data that would capture and map as many aspects as possible, developing proxies for those that could not be mapped directly. For those ESS with multiple data sources, or multiple alternative interpretations of data / ESS sub-models, the hierarchical model may in places be extended to a fourth level or even a fifth level.

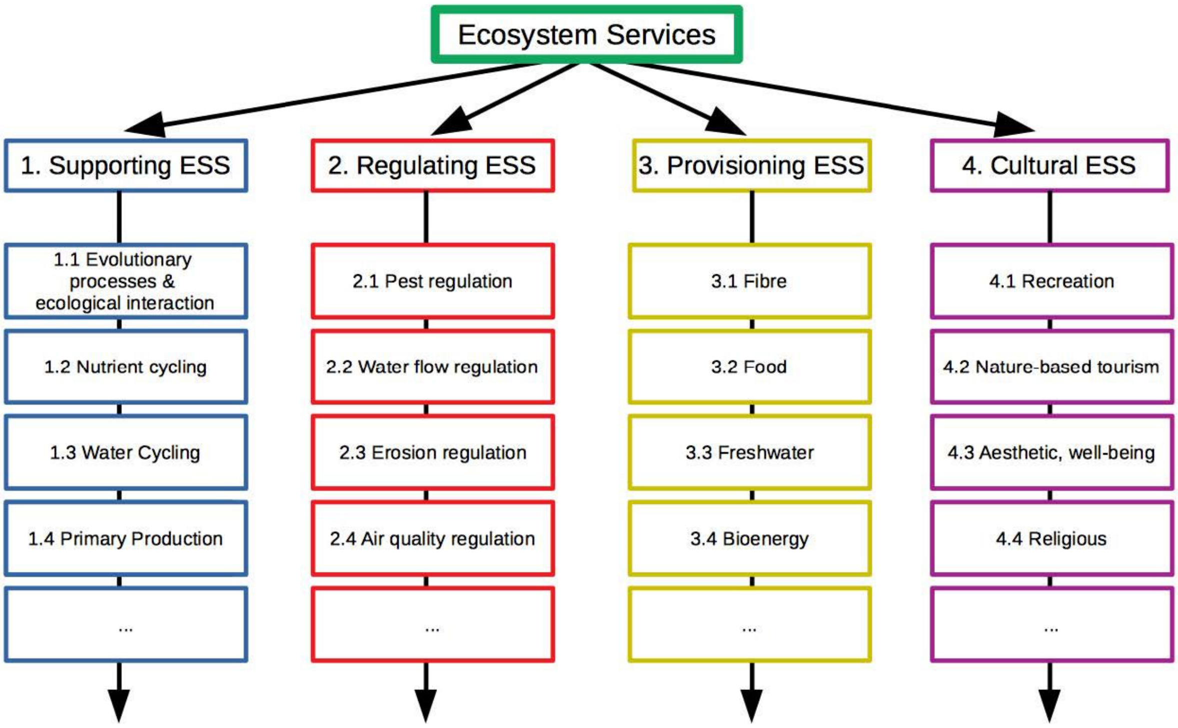

Figure 1. We assigned all of the included ecosystem services a numerical code, where the first digit described the category they belonged to. The inverted tree figure illustrates a few of the different ecosystem services that are included within the four main categories. To visualise the 4th level, imagine a further set of arrows extending from each box to represent subtopics or multiple interpretations i.e. "3.2 Food" could be subdivided into food subcategories (honey, wheat, ...), and then if necessary subdivided further into competing models based on different interpretations or alternative sets of source data. Note that the vertical arrows do not indicate flow of data here, rather, that there are many further ESS topics not shown here.

2.2 The “valuation” of ESS

Based on the data currently available, we accepted that it is not possible to quantify an exact and unarguable value for an ESS in any geographic area. Therefore, we scored estimated contributions to each service based on the available source map data, acknowledging that the true value is more complex than our models, and also that there are also negative contributions or disservices (Vaz et al. 2017). We allowed only three values: 100 for positive contributions to provisioning of a service, minus 100 for negative contributions, and zero when there was no contribution or when the contribution was unknown (and therefore assumed to be average). For example, vegetation belts along waterways scored 100 in the map layer for “provision of clean water”, whilst built-up land scored -100. Forcing a choice between (100,0,-100) for leaf-level sub-models was a deliberate decision, which was discovered early on to be an effective way to resolve dilemmas during the practical discussions of model-building – i.e. matters such as assigning relative value, time-varying value, ambiguous value or potential value. This enabled us to quickly build broad consensus around the first set of data interpretation sub-models for individual services.

The value of the ESS Tree model at a position *p* for a single ESS can thus be represented as:

$f(p) = a_1.f_1(m_1(p)) + a_2.f_2(m_2(p)) + a_3.f_3(m_3(p)) \ldots + a_{1,2}.f_{1,2}(m_1(p),m_2(p)) +$

The valuation at any particular place, $f(p)$, comprises the (weighted) linear sum of many simpler, independent functions involving each of the data sources (here, maps m_1, m_2 etc.) in isolation, or in combination, evaluated at point *p*. Each value a_n represents a weight. The weights may be equal or may be adjusted to represent confidence or preference for a model or dataset. Where complex interactions or synergies exist they are modelled as independent functions of multiple variables. Where alternative views exist in the construction of e.g. the function $f_1(p)$, the function can be decomposed further into a weighted sum of even simpler functions $f_{1a}(p)$, $f_{1b}(p)$...

In the same way, the higher-level ‘group of ESS’ function at point *p* is comprised of a weighted average of individual ESS; and the top level ‘overall value’ function is comprised of a weighted average derived from the values for each of the groups of ESS.

In order to subdivide every issue affecting the overall ESS value into the simplest possible functions, an inverted tree model is used. Anywhere that an 'ESS value' function was felt to be complex, hard to model, hard to implement, or subject to disagreement, it was decomposed into a set of simpler functions combined by weighted average.

This process was repeated until the functions became trivial to implement, an approach known as ‘divide and conquer’ in computer science. From a top-down perspective, the trunk of the tree represents an overall estimate of ESS value for a particular location. The branches, sub-branches and leaves of the tree represent estimates for particular aspects of the overall estimate. The trunk's final value at a position is produced by combining the group of sub-values that represent each major category of ESS. In our model, these major groups were: *Supporting ESS, Regulating ESS, Provisioning ESS,* and *Cultural ESS*. The ESS Tree model makes it easy for different researchers or programmers to work independently on adding or improving leaves or branches, without having to take account of all the other parts of the model. This allows small iterative improvements to the model to be developed by independent teams working in parallel, with each new function instantly available for integration as soon as it is ready.

2.3 A variety of uses for weighted averages within the ESS Tree model

This approach uses weighted averages to combine sub-functions into higher-level functions. Weighted averages provide a convenient, easy-to-understand and easy-to-implement method for combining results of many simple models and are widely used in theoretical model-building and machine learning (Hornik 1991, Leshno et al. 1993, Hashem 1997, Naftaly et al. 1997). Weightings can be adjusted to reflect the usefulness or reliability of each of the sub-models at any point in the tree. For example they can allow new ESS to be included at an early stage of development, but with their effects on the overall model toned down until the data and functions have been checked or tested. Weightings can be used to reflect confidence in a sub-model, or confidence in the datasets that the sub-model uses.

Weightings can also be used to directly model a set of relative preferences of different subgroups of people (researchers, teachers, politicians, the public, hobbyists...) towards each topic and group of topics in the ESS tree model - though for now this remains a goal for our future research and future implementations.

2.4 Points rather than polygons

In combining multiple datasets, intersections between different polygon-based GIS data can create a massive number of polygon fragments representing unique combinations of the source dataset values. We overcame this by defining a fixed set of sampling points, and interpreting each 'leaf layer' in terms of the map area and data surrounding these sampling points. The sampling points were pre-calculated in all of the necessary projections for efficient intersection with all of the source data (efficiency being important due to the large scale and high resolution of the map, and the number of individual maps to be created). A fixed set of sampling points is highly interoperable with other types of data sources, such as raster or point-cloud data, and the density of points can be chosen according to the speed of computer systems, data resolution, area of use, etc. Our present system allows the sampling point set to be quickly varied depending on whether the aim is rapid experimentation with layers (500m grid) or detailed study or public presentation (50m grid). Since the system allows for parallel computation of layers that do not depend on one another, an ordinary office workstation is capable of processing the entire model within 20-60 minutes and providing real-time dynamically visualisable digital map outputs.

2.5 Guiding principles

To design individual ESS leaf layer sub-models within the overall ESS Tree model, guiding principles were used to ensure that layers would be semantically compatible with one another:

Objectivity: To maximise objectivity, and minimise grounds for subjective disagreement, data layers should reflect present use or present quality of land, and not *potential* use or *potential* quality.

Simplicity: ESS should be characterised as simply as possible, using the values -100, 0 and +100. It should be obvious to members of the public that negative numbers are bad, and positive are good. By allowing zero to represent data that is either explicitly 'average' or implicitly 'average' (ambiguous, unknown), the software implementation can be kept efficient. The model output can be initialised to zero everywhere, except where it is known that the landscape is good or bad. Although the values at the leaves of the tree are -100, 0 or 100, when many sub-models are combined in a weighted average the result may take any value in the range between -100 and 100. Therefore, the use of a very simple system at the lowest leaf level still enables a detailed range of map values at the category and overview levels.

Maximum agreeability: Models should be as ‘broadly agreeable’ as possible between all expert participants in order to avoid delays in designing the model, keep implementations simple, and minimise subsequent disagreement about model output and its meaning. Model accuracy can be improved incrementally by future projects focusing upon each ESS topic, adding further nuance.

Normalisation: Results from each weighted average were normalised so that the mean value of the layer was centred on 0. Normalisation is important when combining leaf-level ESS sub-models into higher level ESS category groups, and also when combining groups into a final overview. Without normalisation, anyone viewing the overall result would see an overly 'pessimistic' combined ESS value across the map because most areas are only good at supporting a small number of ESS from the range of all possible ESS.

“The perfect is the enemy of the good”: We considered it acceptable to create a layer that is not especially accurate on first appearance, as long as it helps the estimate of value in general. The key principle was that layers are simple and accessible. They can be updated, replaced, improved, or combined with competing interpretations at any time. Small errors in any area of a leaf-model will be drowned out in the weighted overview. This is because each model contributes only a tiny percentage of the overall total ESS weighted average. Also, the largest and most obvious errors will be those most likely to be quickly noticed and corrected. It is far easier to *build*, *iteratively improve* and then *perfect* a flexible system, than attempt to get an entire large system exactly right from the beginning.

Multiple contribution is allowed: We accepted that some maps and some ESS will contribute two or more times to the overall ESS score. We suggest that this is a natural effect (some areas do contribute in multiple ways) and that selection of weights within the recursive 'weighted average' approach provides a method to remedy the problem where it unfairly dominates the overall view of the map. For example, where two different soil-related layers produce very similar ESS value outputs and are based on the same datasets, they might be assigned a 50% lower weighting each, compared to the weights of the more unique types of layer in that ESS category.

Standardisation of naming: A standardised numbering system was used for each group, topic and model of the tree, enabling consistent identification even with a large number of ESS, and multiple data sources for each ESS. For example, the model of the carbon regulation function provided by forests in the AR5 map dataset, was named “2_5_1” (i.e. regulating function_forest regulation_ model 1). This aided communication by avoiding ambiguity or overlapping work during development.

3 Results

Over 50 ESS sub-models are represented in our model in the four major groups, of which 15 are currently implemented. The data can be presented via an open source map visualisation system, with a standard desktop web interface as well as a mobile interface for phones/tablets. Optional real-time GPS position tracking is available on both desktop and mobile, which enables direct validation of ESS models 'on the ground'. The system was designed to maximise ease of use for new users (particularly on mobile), and to maximise the ease with which new data layers and system features for researchers can be added.

Our resulting map presents the accumulated ESS score for a grid of points in colours from bright green (high positive numeric value) to bright red (high negative numeric value), illustrated in Figure 2. The four main categories of ESS are available as individually selectable map layers that can be added to and removed from the map to explore their relative contributions.

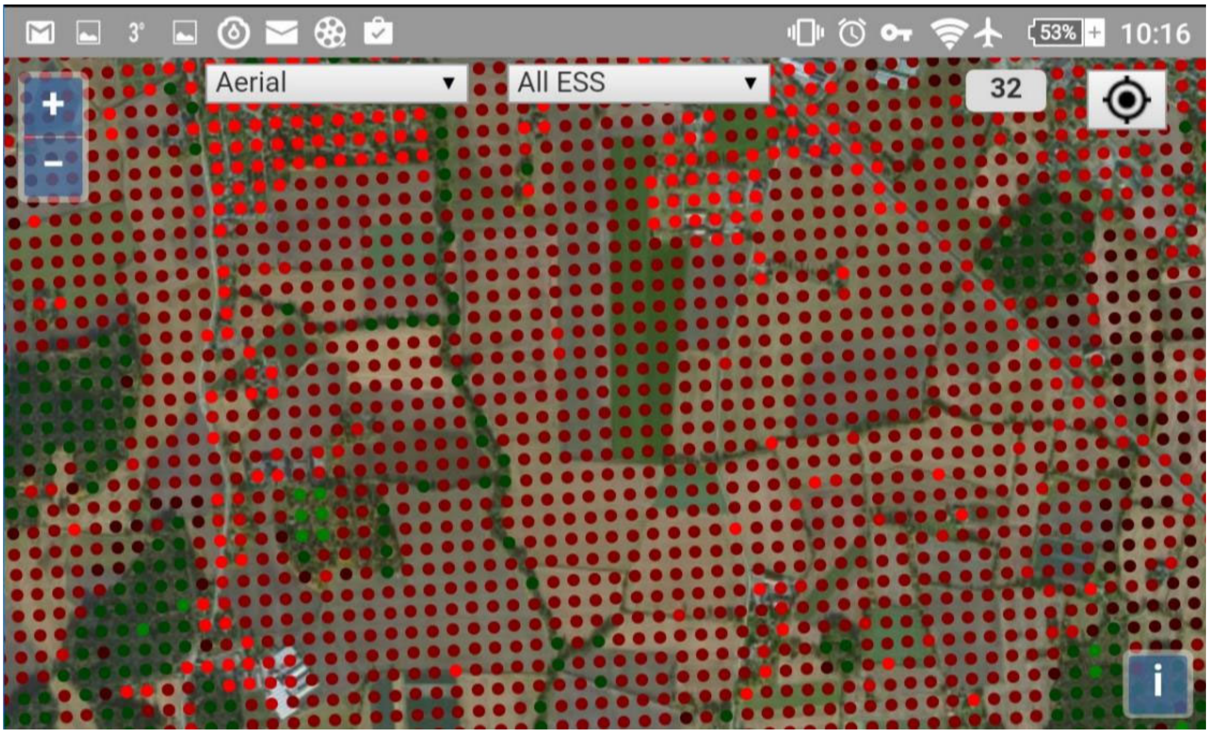

Figure 2. An example of the map view on a mobile phone, displaying accumulated scores for all categories of ESS, against an aerial photo background, with high density of sampling points.

A toggle switch in the corner of the screen provides current GPS position and real-time movement tracking on the map. The colour of the points provides general information about the local area.

Precise information about value at a particular position is achieved by selecting the desired layer and touching or clicking on a particular sample point (Figure 3, overleaf). Current layers and background layers are selected via dropdown menus that fit to the screen on both desktop and mobile systems.

One feature that is still in the process of implementation is the advice system. The idea is that when a user clicks a point, the web system provides appropriate messages depending on both the context of the state of local ESS and the type of user. For example, a farmer who is viewing an area that is in generally good condition but suffers from soil erosion, will be automatically directed to a page with information about how farmers can prevent soil erosion. Figure 3 shows an example for carbon sequestration, where the linked page is a website by the Ecological Society of America explaining more about the topic.

Resultat

NO-MESS	
Comments:	This area scored badly for carbon sequestration. Click here to find out more about carbon sequestration for this type of area.
value	-60

Figure 3. The desktop PC version of the software is shown here. For each point in the map, the total score and additional information / context-sensitive advice can be easily accessed. Here, NO-MESS stands for “Norwegian Map of Ecosystem Services”.

3.1 Open source system

We have open sourced our own work and are offering the data layers implementation, the build system, and the desktop/mobile web map visualisation system as free Open Source software components for anyone to use, re-use, or improve. The components can also be re-used separately for other projects. The database and visualisation interface are freely available for use or modification from Github in the form of zip files for download and as git repositories for programmers (*https://github.com/nibio-ecosystems*). Our own contributions are provided under the MIT open source licence. There are therefore no software licencing issues involved in using or extending the code in other projects. However, we are currently not permitted to share our source data layers freely, so we are exploring ways to open up our own web system and local ESS data in Norway to the public.

We are hosting the software using the "Git" distributed version control system (*http://www.git-scm.com*). This is important, as it enables anyone to take the code and move it in a new direction without seeking approval from a 'gatekeeper'. The implementation of the system relies upon a free Open Source software stack. The GIS layers are implemented using a PostgreSQL database (*http://www.postgresql.org*) with PostGIS extensions (*http://postgis.net*), running under Centos Linux (*https://httpd.apache.org*). The hardware used is an ordinary Dell desktop PC with 4-core 3.3Ghz Intel Xeon, with 32GB ram and 4TB of storage.

A parallelised build system based upon Gnu Make (*https://www.gnu.org/software/make*) is used to allow fast, systematic, parallelised rebuilding of the output layers whenever input data (source maps, sample point positions) or layer models are changed. The system builds leaf models first, then incrementally combines them to build individual ESS, then groups of ESS, then finally the central overview layer. Use of a fully automatic build system avoids the risk of accidentally including out of date models or data into the final overview, and encourages developers to try out their new model implementations as frequently as possible.

Once the model's layers are fully calculated in the database, it is possible to run SQL queries against the model and sub-models. This makes it possible to ask questions such as: Which ESS models score most highly in a given region? Which regions score most highly across many ESS types? How well do results from one ESS model or topic correlate with other ESS models? If a region is 'good' for carbon sequestration, which other ESS tend to score highly (or poorly) in that same area? Exploring such correlations might be a useful way to identify ESS bundles and to predict ESS quality in areas where raw data for some ESS are not available.

3.2 The web and mobile visual interface

A Mapserver client (*http://www.mapserver.org*) connects to the PostgreSQL database and transforms the database layers into WMS web maps. A custom mobile and desktop interface built upon OpenLayers (*http://openlayers.org*) presents the WMS web maps along with information about the ESS being displayed. On the mobile platform it is also possible for the user to centre the visualisation on their current location and follow their physical movement automatically using GPS. For example, a forester or schoolteacher could load the mobile app interface to see which ESS are known to be of high value in a particular area where they are standing.

4 Discussion

In our perspective, a major application of the idea of ESS is to raise awareness of the range of benefits provided by nature, and ensure that land use planning and decision making take due consideration of these values in a timely manner. The final decisions about land use will always be partly political, but they should be well informed by all of the available data regarding where ESS can be provided in the landscape. Land use planning and decision making depend on spatially explicit information. All kinds of data and knowledge are placed on maps, whether it be protected cultural heritage, observations of rare species or areas valued for their beautiful views. In this way, maps have multiple roles in the processes of spatial planning, both by displaying available data and enabling analyses. Areas of conflicting interests can be ranked as a basis for decision-making, or alternative solutions can be tested and debated in scenarios (Fernandez-Campo et al. 2017).

Land use/land cover data is the most commonly used proxy for ESS (Seppelt et al. 2011). Although criticized for not being optimal, this is often the best data available and can be seen as a meeting point between management, planning and ecosystems. It is undoubtedly also a fact that land use and land cover influences provision of a range of ESS. In this context, time is of the essence. Our landscapes are continuously changing, and in our perspective contributing and being able to update information in a timely manner to help make decisions about land use better informed is of the essence.

Maps can be useful tools for promoting communication, identifying and framing important issues, and for analysing the effects of policies. However, there is also cause for caution. The role and intentions of those who create the maps must be transparent, as there have been examples where maps have been used to promote certain interests over others (see Hauck et al. 2013 and references therein). Maps must be well documented to be credible, salient and legitimate to discerning users (see also Cash et al., 2003). They must also convey updated information. Many challenges are of a technical nature (Hauck et al. 2013), e.g. the choice of scale, mapping units and resolution. However, social factors may also influence whether or how maps are used, for example stakeholder characteristics that might make some more likely to use and understand maps than others. Ideally, potential user groups should be asked how they use the maps, with their feedback providing the basis for future improvements to the system and model.

The datasets needed to model a single ESS are often diverse. For example, depending on the type and detail of the study, an accurate model for water cycling might be affected by long term climate models, short term weather models, soil and soil erosion models, terrain/slope models, local tree data, aquatic plant growth, local pollutants, and so on. Challenges include discovering appropriate/relevant datasets, obtaining permissions, gathering the data, and making it available. Even then, there may be accidental or intentional biases or undocumented assumptions that affect how the data can be analysed. Further, different specialist groups may have different understandings of the same data. For example, a botanist's dataset may represent a different understanding of aquatic plants, than that of a sewage management professional. If data are to be meaningfully standardised or integrated into a single research model, these different interests and understandings must be bridged. We also agree strongly with Rodriguez et al. (2014) on the need for monitoring outcomes of management decisions and incorporating lessons learned in future decisions. This relates to another more long-term question of impact: *how can we ensure that these models are actually usable and used, to produce a benefit for society at large?*

The multiple challenges involved in mapping ESS are an unavoidable outcome of the complexity and multiplicity of ecosystems and ESS, and can be summed up as "The Big-Model Problem". The problem is characterized by the large quantity of issues involved, the complexity of the individual issues and their impact on the overall model. Then there are problems of representing very different issues and integrating them. In addition, there are scientific and data management issues, related to gathering and standardising data, and geospatial and spatiotemporal referencing. There are large scale calculations and analyses needed; as well as decisions to be made on storing and archiving and promoting accessibility. The model itself needs to be updated and managed. And finally, the model is of limited use if it is not visualized and understood, or the findings are not communicated to guide decisions and other outputs.

Maps have gained a very important status in planning and decision making. Mapping ESS thus represents an appropriate way of communicating the spatial distribution of ESS. There is a risk implied, however, which is that ESS that are not mapped may be forgotten or overlooked. Our approach is to have a model which aims to include as many ESS as possible and is as easily extensible as possible. This also enables competing views of an ESS topic based on different models or data sources to be kept side by side and combined together with different weightings. At topic level, weighting can be used to indicate the degree of confidence that is placed in each model (or datasource), and at group level, weights can be selected according to the perceived importance of a particular ESS within the group of ESS.

We are not aware of previous approaches to ESS modelling or related technological solutions that are designed to integrate broadly every single field and subfield of ESS study, and that are intended to produce satisfactory results for both small scale and large scale maps, and for studies of individual ESS through to studies of dozens or hundreds of ESS – i.e. broad, general ‘off the shelf’ solutions. This issue of ‘off the shelf’ general models and related technology has been addressed in other scientific fields, where it would now be strange to see an ad-hoc data management and model implementation approach created for each group starting a new project.

The time is right for an ‘off the shelf’ approach to ESS modelling at any scale. This issue has been an important inspiration in the multi-disciplinary effort underlying the work presented here. For example, one of the main factors underlying ease of entry to analysis in the physical and statistical sciences has been the extensive development and common use of open source software in these research fields (e.g. the Fortran and model libraries in Physics, R in statistics, or Spark MLlib and Tensorflow frameworks in machine learning). These have become so advanced and comprehensive that a researcher can test daily thoughts on a scale that would require a large long-term project in many other fields of science.

A distinct set of additional challenges arise when moving from study of a single ESS to a large number of ESS, though – the afore-mentioned Big-Model Problem. These include:

- maintaining coherence between models of diverse services
- broader data acquisition/semantic/GIS alignment problems
- more diverse data standardisation problems
- philosophical problems (what does it mean for an area of land to be good, or bad, or valuable and in need of protection, or poor in need of development, when it comes to viewing 3, 30, or 300 different ESS at national scale in aggregate, as opposed to a single system?)
- subjectiveness (even two researchers in the same group are unlikely to hold identical views about subjective matters of individual ESS, and there may be no correct way to treat an aggregation of many services)
- accessibility to society (politicians, businessmen, teachers, hobbyists, the general public)
- practical implementation problems, relating to the increasing scale and complexity of software/GIS implementations
- keeping pace with change in underlying datasets and research.

For larger projects, a range of technical issues also become relevant, such as data storage formats, storage technologies, whether to use network or data local storage, whether or how often to save backups or time series data, which GIS platform to use, type of computing facilities to use (desktop, cloud, supercomputer) and licensing issues (of software and data), and software version control.

Due to the diversity of professional skills and backgrounds of researchers, and the diversity of source data, it is perhaps unlikely that a single standard for dataset and model exchange will emerge for ESS modelling. Nevertheless, there have already been attempts to improve cooperation between different groups (e.g. Rojas Lara et al. 2015; *http://www.naturalcapitalproject.org/invest/*; *https://www.cbd.int/doc/publications/cbd-ts-77-en.pdf*).

This implementation is still in early stages in terms of the completed data layers at leaf-level (approximately 30 % of the targeted 50+ layers have been implemented). However the technology framework and interfaces of the project are complete. We thus consider it worthwhile to begin to share the system now and invite contributions to further fill it out. Hopefully, others will benefit from this model and technology for their own research and can help fill out the tree with further individual ESS models and extra data sources. The fact that our model is fully “open source” and stored and managed by an organisation responsible for long term land use mapping and monitoring, should provide good opportunities for future testing and development. We thus have less concern that our model will suffer the fate of so many project outcomes in the sciences, which are abandoned as the research project ends (see Sharp et al. 2011). What we present here is the current state of the model, and an invitation to others to help develop this further. We hope that others will get involved, try it out and help make it better.

4.1 Where next?

We see many opportunities for using this system and approach to study ESS and share ecosystem knowledge. However, more work is needed to improve ecosystem models, including obtaining new maps where coverage is low, seeking alternative sources of information (e.g. crowd-sourced data) where data is absent, interpreting data more precisely (e.g. scoring between -100 and 100 into sub-ranges with higher precision), field validation of ESS provision, and cross-referencing each ESS using alternative data-sources and ESS models to identify possible mistakes (data or model errors).

Research is also needed to add 'personal value' modelling, to enable people to interpret the map easily according to their own sense of value and visualise the value preferences of another person or group. This can be achieved by finding out how various groups would set their weightings/priorities for different ESS topics, then combining the topics accordingly. The result would be a map that highlights local areas of special interest to each group based on their preferences. A map area for a field of meadow flowers would be displayed in bright green when viewed through ‘the preferences of a beekeeper’ for example. Potentially this would allow researchers, politicians, and other actors with different priorities to see the world from each other's perspective, hopefully helping to bridge gaps in perception of ESS value of an area, and perceived value of ESS types. One possibility that we hope to explore is to gather relative value weightings by setting up a 'national spending priorities' web-based experiment in which people from various groups (the public, researchers, politicians, educators, businessmen) collectively choose how much they would spend from a national budget on different ecosystem service priorities. The weights derived from the experiment would allow research into how groups view different aspects of ESS. The web map service could lead to better mutual understanding and consensus-building between different groups, particularly when there is conflict over the priorities for preserving or augmenting each form of ESS. This could also allow a more quantitative approach to trade-offs and compromise, wherever ecosystems are under threat at a regional and national scale, or wherever less powerful stakeholders are being sidelined.

5 Conclusion

Whilst the term *ecosystem services* has become commonplace, both in the research world and in key policy documents, it is not an easy concept to explore broadly, either as a research professional or as a member of the public. Even attempts to focus upon a single ESS in a single location can be foiled by the complexity of obtaining, understanding and aligning data and require a broad combination of specialist skills. Our long-term goal is to obtain a better consensus estimate for the state of all ecosystems services across all of Norway by integrating diverse views, and without the need for a central decision-maker at any point. Such integration should lead to better overall estimates, as the average of many informed viewpoints is more likely to converge towards the underlying reality. An integrated system also gives a clearer message to planners and decision-makers who want to use the best available knowledge and feel confident that they understand where the model or data will have ambiguities, conflicts or be incomplete.

This report presents a practical, open source implementation of an ESS Tree model, and we invite other groups to freely compete or collaborate by adjusting or re-using the code to suit their own models of individual ESS or groups of ESS. We cannot guarantee that this tool is without errors, or take responsibility for how it is used by others. Since our project has ended, we are not currently able to maintain or develop this tool. However, by providing the database and visualisation system as free-to-use, open source technologies, we hope to share a technology platform that makes it easy for ESS researchers to put knowledge about ESS into the hands of a wide range of potential users, including teachers, politicians, farmers, developers, land use planners, decision-makers and other researchers. We welcome feedback on our approach (model, data outputs and technology) and hope that it is a helpful step towards a new and practical form of cooperation in ecosystems services model research and development. It is hoped that this work helps lead towards land use planning which better integrates with concerns for all of the key ecosystem services that society benefits from.

Software: *https://github.com/nibio-ecosystems*

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NIBIO
NORSK INSTITUTT FOR
BIOØKONOMI

Norsk institutt for bioøkonomi (NIBIO) ble opprettet 1. juli 2015 som en fusjon av Bioforsk, Norsk institutt for landbruksøkonomisk forskning (NILF) og Norsk institutt for skog og landskap.

Bioøkonomi baserer seg på utnyttelse og forvaltning av biologiske ressurser fra jord og hav, fremfor en fossil økonomi som er basert på kull, olje og gass. NIBIO skal være nasjonalt ledende for utvikling av kunnskap om bioøkonomi.

Gjennom forskning og kunnskapsproduksjon skal instituttet bidra til matsikkerhet, bærekraftig ressursforvaltning, innovasjon og verdiskaping innenfor verdikjedene for mat, skog og andre biobaserte næringer. Instituttet skal levere forskning, forvaltningsstøtte og kunnskap til anvendelse i nasjonal beredskap, forvaltning, næringsliv og samfunnet for øvrig.

NIBIO er eid av Landbruks- og matdepartementet som et forvaltningsorgan med særskilte fullmakter og eget styre. Hovedkontoret er på Ås. Instituttet har flere regionale enheter og et avdelingskontor i Oslo.

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