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A comparison of ecosystem services mapping tools for their potential to support planning and decision-making on a local scale

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ABSTRACT

The inclusion of an ecosystem services framework into planning and decision-making processes is increasingly being seen as a means to further a better implementation of the Ecosystem Approach and to achieve a more sustainable allocation of resources. Tools are slowly emerging to help scientists and practitioners with mapping ecosystem services. This study reviewed three tools with regard to their potential use as standard tools to be employed in local planning. To this end, an email survey was conducted first to identify the most important criteria practitioners require in an ecosystem services mapping tool. InVEST and EcoServ-GIS were then applied to produce several ecosystem services maps for a small catchment in the Scottish Borders. These maps were compared to already existing maps produced with another method, SENCE. We showed that there can be substantial variations in maps produced with different tools. These reflect the differences between the tools, especially in their requirements for data, their user friendliness and their accuracy. Our comparison highlights that tools so far have had to make a compromise between usability and scientific accuracy, which means that practitioners need to carefully weigh the requirements for a specific project before deciding on the appropriate tool.

1. Introduction

Recognition that human society is directly and indirectly dependent on ecosystem services derived from healthy, functioning ecosystems is not new (see for example: Westman, 1977; Costanza et al., 1998; Pearce, 1998; Potschin and Haines-Young, 2011). However, the acceptance of the potential use of the ecosystem services concept in policy-making and management only gained wider recognition with the articulation of the Ecosystem Approach in the Convention on Biological Diversity's Malawi Principles (CBD, 2000) and the production of the Millennium Ecosystem Assessment in 2005 (MEA, 2005) and, for the UK, the National Ecosystem Assessment in 2011 (UKNEA, 2011).

The potential inclusion of the ecosystem approach into management and policy provides many challenges, not least the need to focus on processes and functions of ecosystems and their interdependencies, in order to ensure long-term sustainability. In addition, as Everard (2012) notes, practical approaches are needed to bridge the gap between principles and policies and to ensure implementation through management and decision-making at regional, national and local scales. A key element of this is the requirement for mapping of ecosystem services as part of the process of sorting complex relationships and functions into manageable entities that can be recognized, described, communicated and, to a certain extent, valued, within a spatially defined context.

Policy makers are increasingly recognizing the potential that mapping ecosystem services might deliver for strategic resource planning, and potential means by which to embed ecosystem services into policies and laws have been proposed, such as for the EU Water Framework Directive (Vlachopoulou et al., 2014). Many projects which include identifying and mapping ecosystem services have now been initiated (see the Ecosystem Knowledge Network (http://ecosystemsknowledge.net/). The Scottish Government for example recently initiated two regional pilot projects as part of their national Land Use Strategy, which centres on very detailed ecosystem service mapping as part of an Ecosystem Approach (for details of the Scottish Borders pilot, see Spray, 2014).

These and other studies have shown the need for reliable maps to enable decision-makers to spatially identify areas that supply ecosystem services, to assess trade-offs and synergies between them, and to prioritize areas for specific and targeted management actions. Maps are also a powerful tool for communication (Fish and Saratsi, 2015; Pagella and Sinclair, no date).

To enable ecosystem services maps to be utilized on a routine basis in decision-making, it is necessary to have proven and

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practical approaches to their assessment and mapping. These also need to be transparent as to their scope and limitations. Preferably, this would include a standard approach, so that decision-makers can rely on the outcomes of their analyses, other stakeholders will feel confident in its outputs, and all will be able to share data as well as experiences.

To this end, tools with a variety of foci, application objectives and approaches are being developed. However, comparative studies to investigate strengths and weaknesses of different tools are still very limited, and almost non-existent on a local scale, so there are only limited resources and experience for practitioners to fall back on.

2. Aims

This study firstly reviews three available ecosystem service mapping tools and then compares them by applying them to the Eddleston Water, a small rural catchment within the Tweed UNESCO HELP Basin in the Scottish Borders, UK. A further element of the study was a survey of potential users of ecosystem service maps to elicit their requirements and desires of an acceptable ecosystem services mapping tool.

The aim of the research was to answer the following questions:

1. What are the requirements of practitioners for a commonly applicable ecosystem services mapping tool?
2. What are strengths and weaknesses of the currently available tools?
3. How can these tools be applied in practice?
4. How can we proceed to further a standard approach or tool for mapping ecosystem services in order to support practitioners?

3. Study context

Although assessing and mapping of ecosystem services has grown in the wake of the Millennium Ecosystem Assessment, most studies develop their own tailor-made methodology, so comparability of results is limited. Eigenbrod et al. (2010) and Seppelt et al. (2011) found that most studies used proxy-based methods and that digital raster land cover maps were mainly used as they are widely available. Look-up tables were used to attribute ecosystem service indicators to particular land cover types. Alarmingly, Eigenbrod et al. (2010) go on to show that land cover proxy-based methods reflect actual distribution of ecosystem services very poorly.

Blackstock et al. (2015) further point out that maps of ecosystem services are only as good as the data available, and the choice of services to be included. In addition to often relying on proxies, they are dependent on the scale, scope and date of data, as well as the accuracy and relevance of the algorithms often used to convert data sets to service maps. Data is often missing and projects tend to map the most tractable services, not the full range (Raymond et al. 2009). In addition, criticisms of the GIS mapping approach and its use in catchment management planning note that it fails to deal with issues of uncertainty and with multiple (and possibly conflicting) perceptions when reduced to single maps (Smith et al., 2013).

Mapping of ecosystem services can go beyond biophysical maps to produce mapping of trade-offs, monetary values or services flows. It is important for decision-making to be able to show how ecosystems will react to change and to allow weighing improvement in one service against deterioration in another. Assigning a monetary value can support such cost–benefit comparisons, especially when applied to services that can be assigned a market value (Cowling et al., 2008). They can also support the design of payment for ecosystem services schemes (Schägner et al., 2013).

Approaches for mapping of ecosystem service flows as well as trade-offs are fairly limited so far (Burkhard et al., 2012, Bagstad et al., 2013a, Raudsepp-Hearne et al., 2010, Ruijs et al., 2013). There are more attempts at mapping monetary values, but most studies (78%) use the simplest approach of unit values, and combine this with land cover proxies to arrive at the ecosystem services' supply and unit values. The errors in this method are considered to be potentially very high (Schägner et al., 2013).

In terms of scale, ecosystem services are most frequently mapped at a regional scale (57%), followed by a national scale (Martínez-Harms and Balvanera, 2012). Fewer studies look at a global or local scale, although a more recent review indicates that there might be a shift towards a local or “municipality” scale (Malinga et al., 2015), meaning that experience is growing for mapping ecosystem services at the scale most important for local decision-making and planning. However, for a routine inclusion, standard tools are needed that local authorities can handle.

GIS-based tools are slowly emerging to help scientists and practitioners with mapping ecosystem services. These tools have mostly been applied to a limited number of case studies (Nelson et al., 2009, Kovacs et al., 2013, Villa et al., 2014, Vigerstol and Aukema, 2011, Bagstad et al., 2013b), but interest is growing to use them more widely and there are more examples of trials in a practical context, e.g. the Scottish Borders National Land Use Pilot Project (Spray, 2014) and the Carse of Stirling Ecosystems Approach Demonstration Project (LUC and STAR, 2014).

4. Methodology

4.1. Requirements for tools

Critical to an evaluation of the acceptability of the maps and tools for use in planning and management is an understanding of what success criteria potential users would chose. We therefore invited a range of practitioners, who between them represented the main users across Scotland, to state what they would be looking for in a tool. A total of 27 persons representing different sector perspectives were directly targeted by email and phone to answer a short questionnaire (for full list of institutions and questions please see Appendix I). From the answers received, key points were identified, classified into categories (accessibility and costs, data requirements, user friendliness, stakeholder engagement, outputs, range, scale, reliability, and others) and then the number of times each category occurred overall in the answers was counted.

4.2. Ecosystem services mapping tool selection

In the context of this study we excluded any tools that were not specifically designed for mapping ecosystem services, even if they might seem to have good potential to map individual services (compare for example Vigerstol and Aukema, 2011). It is assumed that only tools with the explicit aim and ability to map a number of different ecosystem services can in the end deliver a satisfactory common method. We further excluded any tools that are not spatially explicit, were still in the early stages of development, have only been tested very restrictively or have been developed outside the UK and are not free of access (see Bagstad et al. (2013b) for a comparative study of further tools).

After a careful review of a range of potential tools against these considerations, we explored two tools in detail, InVEST and Eco-Serv-GIS that were made available to us. A third tool (SENCE),

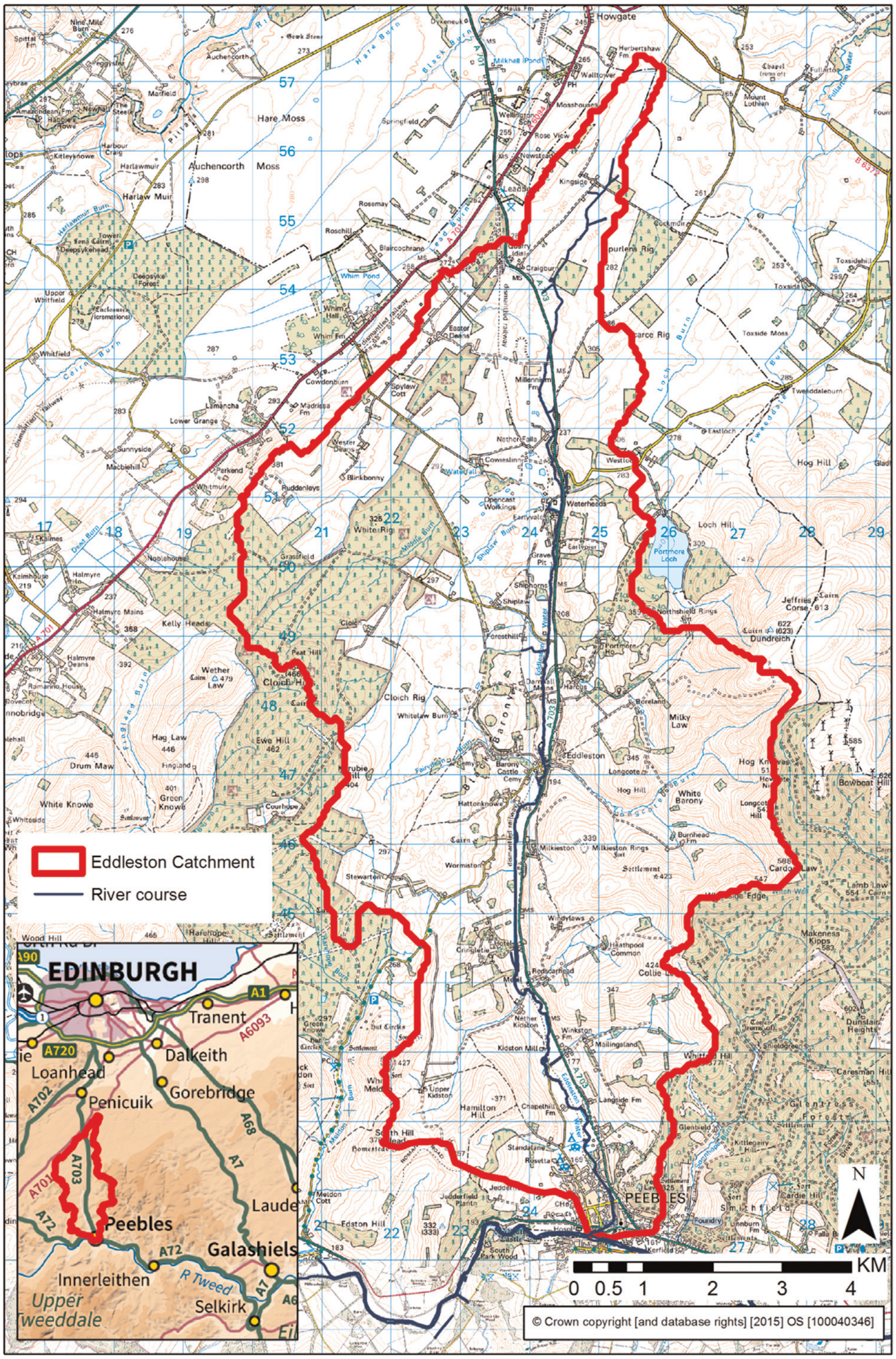

Fig. 1. Map of the Eddleston catchment.

which uses extensive and detailed data was used as a 'control' against which performance of the others could be compared, having been used earlier in the same catchment as part of the Scottish Government's national Land Use Strategy pilots.

In order to evaluate their potential as a standard for ecosystem services mapping on a local scale, these mapping tools were applied to a 69 km^2 catchment in the Scottish Borders, the Eddleston Water (Fig. 1). This is one of the six sub-catchments that were targeted for stakeholder engagement and ecosystem service mapping as part of the Scottish Borders Land Use pilot. Within this, 19 ecosystem services have been mapped for the whole area using the SENCE methodology, utilizing extensive data sets made specially available for the pilots. Drafts of the maps were presented at a series of public stakeholder meetings in Eddleston village to help improve their presentation and accuracy (Spray, 2014). As a result, these "ground-truthed" ecosystem services maps were available to compare with the maps produced in this study and we were able to easily access the necessary datasets for each of the methods utilized in this work, InVEST and EcoServ-GIS.

InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) was developed for global application under the National Capital Project, a Partnership between Stanford University, the University of Minnesota, the Nature Conservancy and WWF and can be downloaded from http://www.naturalcapitalproject.org/InVEST.html. It is relatively well developed and documented, free and easy to access and applicable at a local scale. It is a stand-alone tool and each service is modelled separately. InVEST models are based on land cover and land use patterns and can be used to explore for example the effects of different scenarios of land use (Nelson et al., 2009, Kovacs et al., 2013). They are spatially explicit, using maps as inputs and producing maps as output. The models can be run at different levels of complexity depending on the availability of data and most include an optional valuation model. Results are displayed in quantitative terms, either in biophysical values or in monetary values if the valuation model is utilized. In this study, the valuation model was not utilized as it was not necessary for comparison to other tools that do not allow for it.

EcoServ-GIS was developed by Durham Wildlife Trust and maps the capacity of an ecosystem to supply a service as well as areas of demand for the service on a county scale (Bellamy et al., 2014). Although not developed for a local scale, it offers distinct advantages over other tools, such as the use of readily available datasets and low expert knowledge. It uses available UK-datasets to create a base map assigning a habitat type to each parcel of land. The service models use the base map to create capacity and demand models based on either look-up tables or indicators for ecosystem processes. These maps can then be overlaid to identify areas with flow of ecosystems services.

SENCE (Spatial Evaluation for Natural Capital Evidence) was developed by Environment Systems Ltd. and maps ecosystem services by looking at parcels of land and considering its land cover/habitat type, its geology and soil, its position in the landscape (e.g. steep slope, next to an urban area), and how it is managed. It aims to provide a sound scientific basis by using the best available data. Habitat maps are optimized by combining a variety of data sets depending on what is available and in what detail. Rules are developed based on local knowledge and expert understanding of how habitat attributes deliver ecosystem services, and a relative value (high, medium, low) assigned to each element in each dataset, with weightings applied when different datasets are combined (Medcalf et al., 2012). From this method, maps are derived showing the relative importance of the parcels of land for ecosystem services supply.

4.3. Ecosystem services for mapping

The ecosystem services covered under InVEST, EcoServ-GIS and SENCE are not identical and often consider different aspects/parts of the service (e.g. EcoServ-GIS has a combined model for nutrient and sediment retention whereas these are dealt with separately under InVEST and SENCE). After consideration of comparability, data and time required for the different ecosystem service models under InVEST and EcoServ-GIS, it was decided to produce maps for carbon storage and pollination from both methods, as well as water purification from EcoServ-GIS, to compare against the SENCE results. The exact data requirements and processes to map these services with the two tools can be found in the user guides (Bellamy et al., 2014, Sharp et al., 2014).

Maps for carbon storage in vegetation, carbon storage in soil, pollination resource and water purification regulation (nutrient filtration) were provided by Environment Systems Ltd. with the permission of Scottish Borders Council and could be used without alteration for this study. The necessary data input for EcoServ-GIS was obtained either through the Scottish Borders Council or downloaded if freely available, and adjusted to be used in the toolkit. InVEST required a Land Use and Land Cover (LULC) map, which could be created from a Phase 1 habitat classification map that was also provided by Environment Systems Ltd as part of their work on the SENCE maps. Values for look-up tables were collected from relevant literature. Several look-up tables with varying degrees of detail were created to test the sensitivity of the model.

5. Results

5.1. Requirements for tools

18 answers were received from the questionnaire, with a good distribution between government bodies, local council and environmental NGOs. From these replies, 8 general criteria were identified (in order of frequency of mention):

1. ***Meaningful output*** *(mentioned as important in 83% of the answers)***:** The tool must go beyond the mapping of individual supply maps to promote understanding and knowledge about the relationships between ecosystems and humans, and to better inform decision-making by modelling consequences of change. This can for example be achieved by showing service flow paths or trade-offs/synergies between services, or by placing a value on the service contribution. A valuation must not necessarily be a monetary valuation; however, a means to assess the value gained from ecosystems is often crucial to ensure adequate consideration of the benefits of environmental conservation.
2. ***User friendliness*** *(78%)*: A tool that is heavily reliant on technical expertise (GIS, programming, or ecological) will be a barrier to wide acceptance.
3. ***Stakeholder engagement*** *(66%)*: Maps produced must be easily understandable and offer and encourage debate about land use and management options, and promote participation in decision-making.
4. ***Broadly applicable for a variety of organizations and at different scales*** *(50%)*: As there is a wish to assess and map ecosystem services across a variety of organizations and as part of different decision-making processes, the tool must be able to cope with the resulting range of scales, producing comparable and reliable results.
5. ***Data availability*** *(44%)*: Data that is required by the tool must be readily available or have the potential to be quickly and easily acquired, e.g. by relying on available national datasets, or the tool must be able to cope with data scarcity.
6. ***Transparent and consistent approach*** *(39%)*: In order to be widely accepted, users need to be able to understand how the tool works, what approach is taken and which information is used to be able to interpret the outputs, the reliability and uncertainties.
7. ***Low costs*** *(39%)***:** Costs can occur through a variety of factors, e.g. by relying on expert input, being time consuming, needing costly data or commercial software or by access being restricted (not free). If the tool becomes too expensive to run, it will not be applied widely.
8. ***Range of services*** *(39%)*: Which services are essential for any one study will largely depend on the specific context of the mapping and the region. Furthermore, the definition and classification of services is still subject to debate. However, all responders wanted a tool to be able to be applied to a range of services, and not just cover single types. It was felt that a pre-selection of services would bias decision-making and undermine the process of stakeholder engagement. Therefore, no

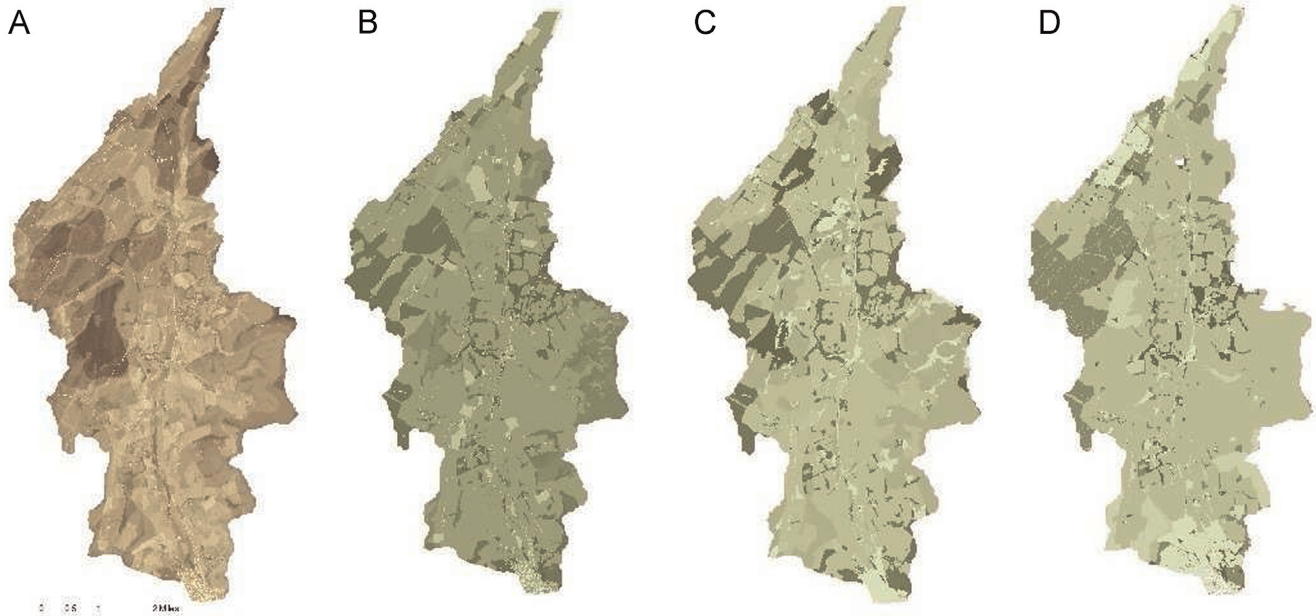

Fig. 2. Eddleston ecosystem services maps: carbon storage mapped with SENCE (soil and vegetation), InVEST and EcoServ-GIS. A. Soil carbon resource mapped with SENCE. The map shows areas where land has the potential to store carbon in the soil. Dark colours represent areas with high level of organic soil carbon and where vegetation supports carbon storage in the soil. Light colours represent soils with little organic carbon. B. Vegetation carbon resource mapped with SENCE. Dark colours represent areas where carbon is stored in vegetation. Light colours represent areas where carbon is removed from the land each year (arable areas). C. Carbon storage mapped with InVEST. Dark colours represent areas with high storage values for carbon including above-ground and below-ground vegetation, soil and dead matter. Light colours represent areas with low values for stored carbon. D. Carbon storage mapped with EcoServ-GIS. Dark colours represent areas with high storage values for carbon in above-ground vegetation and soils. Light colours represent areas with low values for stored carbon. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

services are identified here that a tool should definitely cover. However, it can be argued that a tool should cover services from all four categories (provisioning, regulating, supporting, cultural) to be able to balance different demands, and leave scope for the incorporation of further models.

5.2. Ecosystem services maps and tools review

5.2.1. Carbon storage

To assess how well the tools mapped the amount of carbon stored in ecosystems in the Eddleston catchment, maps were produced with all three methods (Fig. 2). SENCE distinguished between soil and vegetation carbon whereas these carbon pools are combined in InVEST and EcoServ-GIS.

All maps coincide for areas of forest which score high for carbon storage. EcoServ-GIS however does not distinguish between recently felled areas of woodland and other woodland, displaying these areas as having high storage capacity. Apart from that, the maps show a good resemblance especially for small patchy areas of woodland and scrub in the river valley. However, a difference is observable for areas of dry heath/acid grassland, with EcoServ-GIS scoring this habitat as having low carbon storage capacity, in contrast to SENCE and InVEST. Bog areas score very high in InVEST, but as there are no bog areas identified in EcoServ-GIS, the two methods cannot be compared with regard to this. Although bogs do not score highest in the SENCE vegetation carbon storage map, areas where bog is present score high for soil carbon in SENCE.

As information on land cover is the main input characteristic for all tools to assign carbon storage values, similarities are not surprising. Differences are due to **differences in values assigned to habitats**. EcoServ-GIS might also differ due to the **identification of parcels of landscape as different habitat types** compared to that in SENCE and InVEST.

SENCE incorporates information on actual soils present, as well as habitat effect on carbon soil storage in the soil carbon map. In contrast, however, both InVEST and EcoServ-GIS can only consider the effect the vegetation has on the soil's capacity/potential to store carbon, but do not consider the actual soil type present in the area. This means that any potential differences in the carbon stored in soils within the same habitat classification depending on where it is actually situated, cannot be picked up with these two methods. For bogs, this might not be a big issue as these will only occur on a small range of soil types; however, the effect might be more marked in woodlands and forests or grassland, leading to inaccuracies.

Apart from effects of the soil, there are other variables that might influence the capacity of a habitat to store carbon, including the age of the woodland, its elevation, species composition and land management (Morison et al., 2012). Of these, land management is incorporated in SENCE to a certain extent, depending on the availability of data. Age of the woodland is also reflected in SENCE and EcoServ-GIS by using the Ancient Woodland Inventory to identify areas of old woodland. InVEST offers the possibility to incorporate some land management information through identifying areas that produce wood products (harvest rates for each parcel); however, this has not been used here. Potentially, both InVEST and SENCE could incorporate more detail, for example by further distinguishing habitats and their management and accordingly adjust values entered/rule-bases used. However in practice this would require very detailed data input that is infeasible for application in a standard process. This emphasizes that the maps need to be interpreted as showing potential storage capacities rather than actual storage.

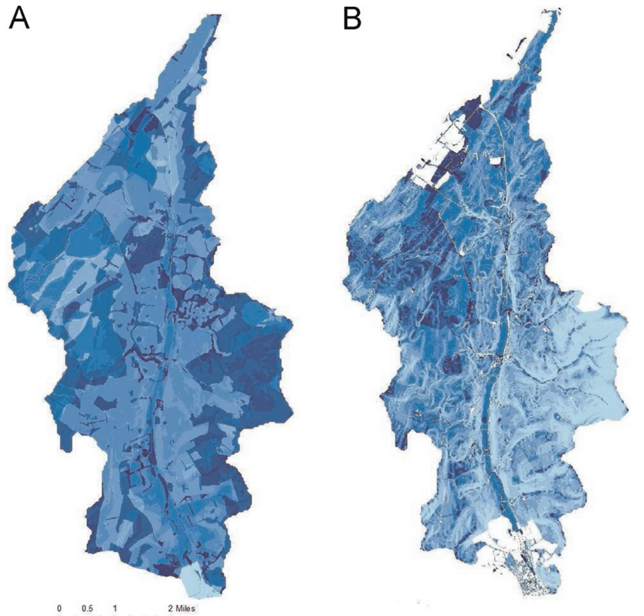

Fig. 3. Eddleston ecosystem services maps: water regulation mapped with SENCE and EcoServ-GIS. A. Regulation of water quality mapped with SENCE, showing the contribution of land to the filtration and supply of freshwater. Dark colours represent areas that contribute to water filtration. Light colours represent areas that may be inputting impurities to the water environment. B. Water purification capacity mapped with EcoServ-GIS. Dark colours represent areas that potentially contribute to the filtration of water due to slowing water flow down by rough surfaces and shallow slopes. Light colours represent areas with low potential for water filtration due to steep slopes and smoother surfaces where water runs off quickly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.2.2. Water purification

The potential of areas to support water purification was mapped with SENCE and EcoServ-GIS (Fig. 3). The two maps differ markedly and only show broad similarities especially with regard to the Northwest of the catchment, where large areas of woodland occur. The biggest difference in the two maps can be observed for the steep Eastern part of the catchment. SENCE here shows a relatively high capacity for water purification, identifying the area as mainly dry dwarf shrub heath, whereas EcoServ-GIS shows low capacity, identifying it as grassland and having a steep slope.

The EcoServ-GIS model includes nutrient and sediment removal, whereas SENCE only looks at nutrients and maps potential for sediment removal separately. EcoServ-GIS highlights areas that have maximum potential either to improve water purification capacity (by changing vegetation structures in areas of shallow slope) or to mitigate pollution in areas that might contribute (by improving surface roughness in areas with steep slopes). SENCE by comparison places more emphasis on the types of habitat that contribute to water purification, but would also highlight areas where soils can contribute or might be detrimental.

Some differences in the maps show the effect of uncertain habitat classification. In EcoServ-GIS, the potential for water purification of the heathland area in the East is certainly underestimated. Overall, the differences in the maps are probably mainly due to differences in the drivers identified for water purification and hence **different approaches to determining service delivery**. Although slope is included in the SENCE maps, a bigger influence is assigned to habitat type and soil type. In EcoServ-GIS, slope is a key driver for mapping the service.

5.2.3. Pollination

Pollination as an ecosystem service was mapped with all three methods for the Eddleston catchment (Fig. 4). There are some similarities between the SENCE and the InVEST maps, for example showing high importance of dry dwarf shrub heath for the service. Woodlands are displayed as having low value in SENCE, whereas the InVEST tool here distinguishes between woodland patches depending on the size (showing high value for small areas and edges, with decreasing value towards continuous areas of forest). This difference arises from the fact that SENCE displays potential presence of pollen bearing species, therefore assuming these areas

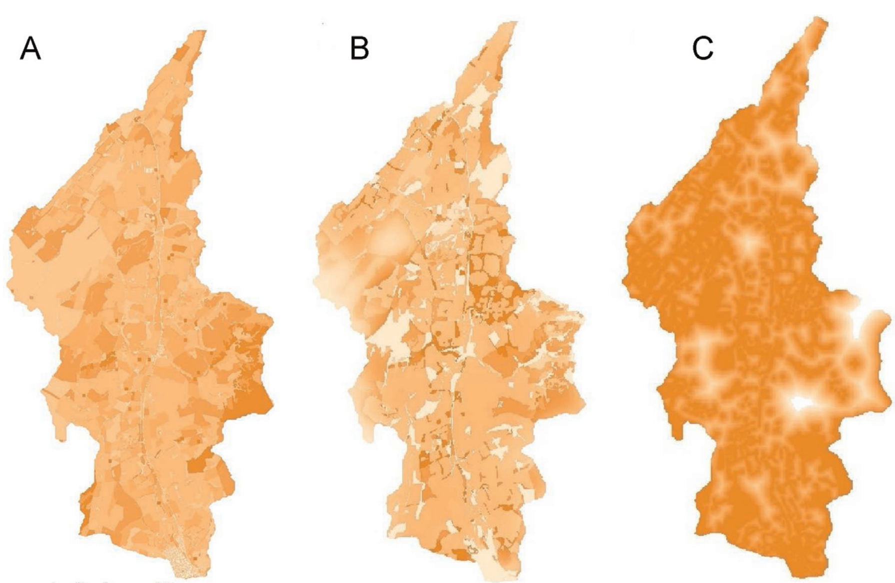

Fig. 4. Eddleston ecosystem service maps: pollination mapped with SENCE, InVEST and EcoServ-GIS. A. Areas important for pollination mapped with SENCE. The map shows areas likely to contain pollen bearing plant species and thus supporting a range of pollinator species. Dark colours represent areas most likely to support pollinator species whereas light colours represent areas with little support for insect pollinators. B. Areas important for provision of pollination mapped with InVEST. Dark areas show habitats likely to provide pollinators with food and/or nesting opportunities whereas lighter colours represent areas with little potential to support pollinating bee species. The calculation includes the likelihood of pollinators to reach habitats based on an average distance covered when foraging of bumblebees and three families of solitary bees. C. Pollination capacity mapped with EcoServ-GIS. Dark colours represent areas close to edge and full habitats whereas light colours represent areas further from edge and full habitats. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as having a high likelihood of supporting pollinators. InVEST also uses the approach of habitat as having the potential to support pollinator species but includes the provision of nesting habitat, leading to woodland edges receiving a higher score. So a **difference in approach to determining the ecosystem service** is observable again here.

The EcoServ-GIS map for pollination capacity shows a high capacity almost all over the catchment, with the exception of a patch towards the Southeast of the catchment and at the Eastern border. As EcoServ-GIS maps the distance from edge (habitat such as woodland where only the edge is suitable e.g. for nesting) or full (where the habitat is used in full, e.g. grassland as forage habitat) pollinator habitat, this means that almost all of the area is identified as being in reach of a suitable habitat. Areas that score highest are woodland areas and dry heath/acid grassland, with the value decreasing with increasing distance (independent of habitat). Areas where the habitat classification is uncertain seem to be scoring lower (e.g. undefined grassland).

SENCE includes information on species composition and presence, making the maps more specific to the site, whereas InVEST only distinguishes by habitat type, potentially leading to uniformity errors. **Additional data** therefore support the reliability of the SENCE maps. In EcoServ-GIS, the effect of habitat is less clear but the effect of distance from a habitat generally identified as important for pollinator species is very dominant. This means that EcoServ-GIS generally conveys a **different message**, as it would highlight that breaking up landscapes and including small patches of suitable habitat would increase service supply, whereas especially SENCE would emphasize the importance of habitats that support pollen bearing species for the service. In InVEST, both effects are observable.

None of the methods is really capable of including very small features in the landscape that can have huge benefits for the provision of pollination, such as small strips of hedgerows or wild flowers. However, SENCE includes hedges if data is available. InVEST could also include these features if the LULC map is adjusted to an appropriate resolution.

5.2.4. Origins of differences

In InVEST, the basis for calculating ecosystem services supply is a Land Use and Land Cover map that needs to be provided by the user. SENCE equally relies on the provision of a habitat map. The habitat map used for SENCE and in InVEST in this study is the same; therefore differences in the output maps cannot be due to variations in how habitat types have been assigned, but must be down to either different data in the look-up tables (as for carbon storage), different approaches/rules to calculate the provision of a service (as for pollination), or the use of additional data sets in one of the models (as for carbon storage and pollination).

For EcoServ-GIS, however, the tool created its own habitat map. Hence, differences between EcoServ-GIS maps and SENCE and InVEST maps can also arise from different habitat classifications. It can be assumed that both habitat maps (the provided one and the created one in EcoServ-GIS) include errors. As the SENCE/InVEST habitat map was provided rather than produced within this study, it is more difficult to judge how reliable the habitat classifications are. However, the SENCE maps have been validated by stakeholder review and consultation, so it can be assumed that many potential mistakes in assigning a land classification have been minimized. Therefore, the SENCE map is accurate enough to suggest that misclassifications have occurred within the EcoServ-GIS classification especially with regard to the omission of heathland, bogs and for some grassland areas.

In essence, differences observed between the three maps can basically be described as originating from one of these sources:

1. Different classification of habitat to a parcel of land.
2. Different values ascribed to the habitat with regard to service provision.
3. Different approach to how ecosystem service delivery is determined (rule/algorithm used).
4. Additional dataset(s) used in any one tool.

6. Discussion

6.1. Requirements for tools

Responses received from the questionnaires about the criteria for a standard tool, although highly individual, had common themes that enabled us to identify key criteria with some confidence. Whilst it is acknowledged that these were derived from a targeted group of individuals from one country, the range of respondents and their involvement with ecosystem service policy and practice was good. Requirements of course may differ slightly according to the precise context of application of a mapping tool and the legislative and governance structures for planning and implementation.

6.2. Ecosystem services maps and tools review

The extensive review of ecosystem services maps by stakeholders, as happened with the Eddleston ecosystem services maps produced with SENCE, is rare among mapping studies, as it is expensive, difficult and time-consuming to do. It leads to an increased confidence in the maps, although it is recognized that there may still be some inaccuracies in the underlying data. This has not been tested further in this study, for instance by going back to primary data sources. Therefore, we are limited to analysing comparative accuracy of the maps and tools, rather than absolute accuracy.

Overall, it is clear that none of the tools so far can satisfy all the requirements from users (see Table 1), but are focused to perform well in certain areas and hence compromise on others.

The consultancy-developed and applied method SENCE stood out by including the largest range of datasets and by an approach that carefully balanced the necessity of conveying usable information on where a service is generated, and the limitations in assessing and mapping it scientifically accurately and reliably. This leads however to a larger amount of required time and resources.

EcoServ-GIS provides a very user-friendly tool insofar as it uses datasets that are mostly readily available and requires only an intermediate level of GIS knowledge. This makes it very apt for a rough assessment of larger areas. It is however less transparent

Table 1
Overview of how tools perform against identified stakeholder requirements. Symbols: + = high potential; o = medium potential; - = low potential; ↗ = scope for improvement.

Criteria	SENCE	EcoServ-GIS	InVEST
Display of service flows and/or trade-offs/ synergies	o	+	o
Valuation of ecosystem services	-	o	+
User friendliness	n/a	+	o
Stakeholder engagement	+	o	+
Applicable at a variety of scales	+	o	+
Data availability	-	+	o
Transparent, reliable approach	o	o	+
Low costs	-	+	o
Range of services	+	↗	+

with regard to the underlying values and algorithms, and uncertainties in data are less easy to spot and remedy especially for a low expert user.

InVEST is a very flexible tool with regard to scale, data input and detail of assessment and mapping. Whilst it can be well adjusted to the specific site it will always rely on a large amount of accurate data. It offers the additional possibility to include monetary valuation.

SENCE tries to alleviate uniformity errors by the inclusion of as much local data as possible, but at the cost of being a lot more time-consuming and costly. Any tool with the potential of standardization in the sense of being quickly and easily applied, as offered by EcoServ-GIS, will by necessity have to fall back on generalized data that will always carry a greater risk of errors and inaccuracies. InVEST carries this risk too, although it can be better controlled by the user through more control over the data input (which could include primary data). In any case, users need to be aware of the limitations of each mapping tool, and interpret maps accordingly.

7. Conclusion

7.1. What are the requirements of practitioners for a commonly applicable ecosystem services mapping tool?

It is recognizable that what is commonly desired is a proven, standardised approach that covers a wide range of services and scales and that can be utilized with readily available data whilst producing clear and intuitive results.

7.2. What are strengths and weaknesses of the currently available tools?

The tools investigated here have been developed with different foci and hence differ in the areas for which they perform well and where there is scope for improvement. So far, the tools cannot match all identified requirements. Tools that try to offer a high amount of reliable data and scientific accuracy take a long time and are costly to apply. Tools that try to satisfy the demand for quick and cost-effective assessment and mapping compromise on accuracy.

There remain a number of key challenges for any one tool in terms of achieving all of the suggested criteria:

1. Our knowledge about how ecosystems deliver many of the services is still limited, as is knowledge about interactions between services. As observed, tools differed in the algorithms and rules that were applied, leading to different outputs and uncertainties, as well as simplifications in the resulting maps.
2. The data available for input can vary hugely in resolution, detail and quality, again accounting for differences, generalization and simplification.
3. The more that tools try to reflect the complexity of ecosystem services delivery, the more expert knowledge is usually required of the user, including the incorporation of detailed local conditions. These tools are likely to be more costly and time-consuming.
4. Ecosystem services maps will often be used as a basis for discussion with non-experts and must therefore be easily understood. However, due to generalization and simplification, maps often display proxy information, as well as representing potential rather than actual delivery. This adds to the difficulty of interpreting maps appropriately.

We need to ask if it is actually possible for one tool to meet all demands. As ecosystems are complex and the provision of ecosystem services is dependent on a large variety of factors, many of which are not yet completely understood, cannot be measured directly, or for which data is not yet available to represent them, assessing and mapping methods are characterised by compromises between what is needed, desirable, practicable, and possible.

7.3. How can these tools be applied in practice?

If, as is clearly desirable from end-users' perspectives, we want to progress to identifying an agreed standard for ecosystem services mapping, a consensus needs to be reached on the balance between resources and time on the one hand, and the necessary accuracy and reliability on the other. This balance needs to reflect the context in which such maps will be used and how they will practically be applied. This will help identify acceptable trade-offs and show more clearly in which areas existing tools could usefully be applied, how existing tools could be developed further or where new tools are needed to meet the demand for other areas of application. At the moment potential users will need to identify the specific use for the maps and determine which aspects are most important. This will enable them to choose the tool best suited to the project.

7.4. How can we proceed to further a standard approach or tool for mapping ecosystem services in order to support practitioners?

Whilst some of the challenges can potentially be addressed through further research into ecosystem functions and modelling, we recommend that more trials are undertaken of tool application in practice despite the current limitations to further study the benefits and challenges of ecosystem services maps in planning and decision making routines. The observations then need to feedback into further developments of tools.

Map copyright

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Appendix

A Questions of the email survey

1. Without looking at question 2, please list the five most important key factors that you would look for when deciding what ecosystem mapping method to use.
2. How important would these criteria be for you, in terms of high (h), medium (m), low (l)?

Usage of only freely available data.

Flexibility of the data required (e.g. would work with different resolution DEMs, depending on what is available).

Advanced stage of development and reliability (would you only consider a tool that is comparatively far developed and tested so that its reliability under specific circumstances is known?).

Flexibility with regard to application for different scales and regions.

Large number of services mapable.

Not much time required.

Low expert knowledge required.

Free access.

Low costs.

Quantitative results.

Display of services flow.

Display of trade-offs between services.

Possibility to map opportunities.

Easy to understand for a wider public.

Any other comments or important points?

B Institutions from which answers were received

Scottish Natural Heritage (SNH), Scottish Environment Protection Agency (SEPA), Joint Nature Conservation Committee (JNCC), Centre for Ecology & Hydrology (CEH), Natural England, Aberdeenshire Council, Perth & Kinross Council, East Lothian Council, West Lothian Council, Tweed Forum, Wildlife Trust, Plantlife, National Farmers Union Scotland (NFUS).

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