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Further development of a spatial framework for mapping ecosystem services

Briefing paper 5 - Multi-benefit and opportunity mapping

Medcalf, K., Small, N., Finch, C., Williams, J., Blair, T., Haines-Young, R., Potschin, M. & Parker, J.

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For further information please contact:

Joint Nature Conservation Committee
Monkstone House
City Road
Peterborough PE1 1JY
http://jncc.defra.gov.uk

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Contents

1 Introduction

Benefit[1] and Opportunity mapping (BM and OM respectively) can be considered as part of a larger family of GIS methods that aim to combine different layers of geographical or environmental data to make an assessment of some kind. Broadly equivalent but more widely used approaches include 'suitability' and 'constraint' mapping, but in the most general sense both could be considered as particular examples of spatial modelling. The differences between these methods are not so much the generic nature of the underlying techniques, but rather in the thematic areas in which they are applied.

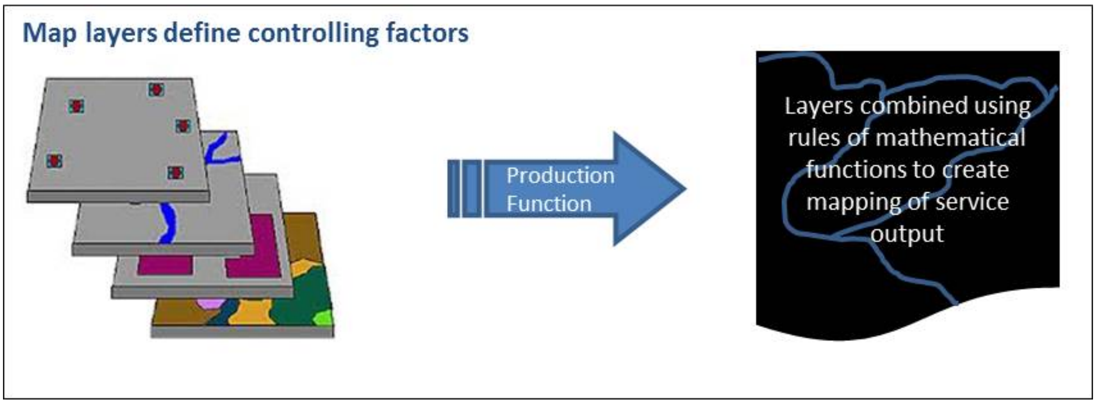


Figure 1. Overlay approaches for benefit and opportunity mapping.

Opportunity mapping, for example, could be viewed as a more specific kind of constraint mapping method. In the context of the present study, therefore, we may wish to map where the output of particular services might be expected, based on a range of inputs, such as habitat type, substrate, management, and geographical location. These separate data layers can be considered as a set of constraints which when combined through some kind of rule-based map overlay technique can be used to predict the varying level of service output (Figure 1). Such rule-based approaches can involve weighting the influence of the different map layers, and can result in complex map-algebra operations or models. Such methods broadly conform to the notion of a 'production function' as described in the ecosystem services literature, that is a method that uses information about the structure and function of ecosystems to estimate the output of an ecosystem service. Using such methods, the outputs can be described as 'opportunity maps' in the sense that they might help identify where a particular ecosystem service might be enhanced by modifying one of the constraints (e.g. management) through some kind of intervention.

Benefit mapping, on the other hand could be viewed as a particular example of 'suitability mapping', in the sense that the aim here is to identify which locations are most likely to be of value in some way to people. Such maps could be derived directly from those depicting an ecosystem service where the service-benefit relationship is well established, but may also involve the combination of these data with additional constraints to predict spatial patterns in value. For example, a habitat map might be used to identify the location of sites that, in biophysical terms, are capable of supplying a service such as recreation. To understand the particular benefits that these sites provide, however, may require information about their location in relation to where people live, the distance they are prepared to travel and/or how much they spend during a visit. As we will see, benefit mapping may be accomplished by first using a production function to model the output of ecosystem service and then proceeding with a valuation exercise of some kind. As Tallis and Polasky (2009) note

[1] For convenience we will use the terms 'benefit mapping' and 'multi-benefit mapping' as meaning essentially the same thing – although note that consideration of several ecosystem services provided by the same ecosystem is a particular emphasis of the current brief.

however, such studies often require detailed, site specific information that is either often not available or too expensive to collect. In these situations 'benefit transfer' methods might be used to undertake the mapping. This method uses the value estimates that have been made in other settings and applies (or transfers) them to another, with adjustments to take account of any differences. Thus the method does not model the output of ecosystem service at the locating directly, but directly infers their value by arguing that situations are somehow analogous.

Although we have located opportunity mapping as one of a wider set of constraint mapping techniques, and suggested that benefit mapping is similar to suitability mapping, there is clearly little difference between them in terms of methodology. As our review will show, they all draw on a range of different analytical tools; all of them depend on combining different spatial themes in some way. For clarity, if these terms are retained in the present study, it is recommended that the intention should be to identify different types of application rather than method, thus we suggest that:

Opportunity Mapping is used in those situations where, for example, the intention is to identify spatial variations in some 'final ecosystem service' derived from a set of underlying functional relationships. These would be the kinds of map that would result by combining the various soil and vegetation factors used in the *Ecosystem Spatial Framework Database,* to predict where a particular ecosystem service might be anticipated. The notion of 'opportunity' could be extended in this type of application by considering where the output might be enhanced by modification of the current management regime. Such uses would be typical of the wider use of suitability mapping methods to explore 'what-if' questions in a decision support role.

Benefit mapping is used specifically for those situations where the value of an ecosystem 'good' or 'benefit' is being considered. This terminology follows the UK NEA[2], which regards benefits as the direct and indirect outputs from ecosystems that have been turned into products or experiences that are no longer functionally connected to the systems from which they were derived. Benefits are therefore things that can be valued either in monetary or social terms. This kind of analysis can be extended to look at the 'multi-benefit' situation, where 'bundles' of benefits that might potentially be derived from a given area, and the synergies and trade-offs that might exist between them.

In both cases the analytical approaches applied can be complex, and in this sense can best be viewed as a form of spatial modelling in its broadest sense. The spatial analysis of ecosystem services and their benefits is one of the most active areas of current research within the field and, as initiatives such as MAES in Europe demonstrate[3], one that is of particular interest to policy makers. In the remaining parts of this briefing paper we provide an overview of the generic set of methods that can be used to undertake benefit and opportunity mapping. We also provide a short review of the applications that can be found in the current literature. In the final part of this paper we identify some of the implications from the current study.

[2] http://uknea.unep-wcmc.org/

[3] Maes (2012): Mapping and Assessment of Ecosystems and their Services. An analytical Framework fro Ecosystem Assessments under Action 5 of the biodiversity strategy to 2020. Discussion paper – draft version 9.6 Reference

2 Overview of opportunity and benefit mapping methods

Modern GIS systems offer a wide range of functionality, and such versatility means that there is no simple way of classifying the different methods that can be used for constraint and opportunity mapping. For the purposes of this briefing paper we have extended the typology suggested by Malczewski (2004, 2006) and added participatory methods to the three basic categories originally suggested, which were: overlay mapping; multi-criteria analysis (MCA); and artificial intelligence (AI). We have also extended AI methods to include Bayesian techniques.

2.1 Overlay mapping

Overlay analysis is one of the most basic, and well-established methods available in the GIS toolkit. In simple terms it involves intersecting a series of thematic layers to create new spatial units whose properties depend on the combination of factors used to create them. Thus if a set of vector-based maps are used, the intersection of the different polygon layers can be used to define some new vector coverage. Alternatively, with raster maps, pixels in a new data layer can be created based on combinations of the properties of a series of input layers. Such methods can therefore be used to generate both opportunity and benefit mapping for ecosystem services, providing some underlying logic can be developed around the way the different layers should be combined.

Overlay methods have been widely used to produce land suitability maps of different kinds. Their popularity mainly rests on the fact that by relying on ‘standard’ GIS functionality, they are easy to implement, and easy to understand especially by the non-specialist. The methods available can vary considerably in their sophistication, however, with simple Boolean overlay giving rise to more complex ‘map algebra’ techniques, involving combing data layers using weights and/or mathematical functions. Using map algebra, for example, the strength of influence of the different input data layers can be varied.

Examples of this use of these methods for opportunity mapping include the estimation of ‘carbon sequestration’ based on using standard carbon densities for different habitat or land cover types and area or stock estimates, in the Polyscape (Jackson *et al* 2013) and InVEST systems (Tallis and Polasky 2009). More complex modelling operations are illustrated by the estimation of erosion potential (and hence the mitigating effects of land cover or habitat on such hazards) using the universal soil loss equation (USLE) using InVEST (Tallis and Polasky, 2009). The latter estimates the average annual soil loss (A) as the *product* of rainfall, runoff erosivity, soil erodability, slope length, crop management and a factor expressing the degree to which management practices limit erosion. In Polyscape, the erosive potential of overland flow is estimated by the so-called ‘Compound Topographic Index’ (CTI), which is the product of overland flow, magnitude, slope, and overland flow concentration (Jackson *et al*, 2013). Alternative and more general approaches to mapping the demand and supply of ecosystem service using a simple production function approach is illustrated by Burkhard (2011), Crossman *et al* (2013), Kienast *et al* (2009), and Haines-Young *et al* (2012), which all employ a simple lookup-table to identify potential service outputs to underlying ecological structures and functions.

Although suitability and constraint mapping based on overlay and map algebra methods continue to be widely used, they are not without their dangers. As Malczewski (2004) cautions in terms of these kinds of methods in general, classical Boolean operations and weighted linear methods can be criticised because they tend to oversimplify processes. A limitation is that they often focus on the things that can be represented in a GIS, rather than the factors that really influence things ‘on the ground’. Malczewski (2004) suggests that there are many examples of mapping based on untested or unverified assumptions. In addition the lack of independence between input criteria may make the application of statistical methods invalid. This can lead to a poor understanding of the way measurement errors are propagated through the calculation steps and hence the level of uncertainty in the mapped outputs. Such problems are not exclusive to suitability and constraint mapping, but apply to modelling techniques in general. In their account of models within the InVEST system, Tallis and Polasky (2011a,b), suggest that modelling approaches used to map ecosystem services and values based on underlying production functions can be described in terms of a set of ‘tiers’. They use this framework to contrast simple models based on readily available, and sometimes generalized data, where models are more complex and more demanding in their construction and data requirements. Because of their simplicity, models at the lowest tiers are generally more easy to understand but more prone to error. Tier 2 and 3 type models, on the other hand, are time consuming and difficult to apply, but are often capable of describing real outcomes at specific places. Tallis and Polasky (2011a,b) argue that all types of model have their role. The challenge is to understand the requirements of different decision-making contexts, and what is gained in moving from simple to more complex approaches.

2.2 Multi-criteria decision making methods

Malczewski (2004) argues that many of the problems of simple overlay methods for suitability and constraint mapping can be overcome though the use of ‘multi-criteria methods’, which involve the use of explicit ‘decision rules’ that define the relationships between multiple inputs and outputs. In reality, these approaches are no different to the methods described above, except that they are more transparent about the assumptions on which the calculations are based. It is also argued that they can overcome the problem of ‘subjectivity’ in terms of the way the different inputs are weighted, by basing these on preferences specified by the user. Two broad sets of MCA approaches can be identified: multi-attribute and multi-objective.

Multi-attribute methods are, like the overlay approaches, primarily driven by the availability of data. In many ways they are an extension of these other techniques except that the way the data are combined is driven by a set of decision rules, often designed by the user, rather than by the application of a simple algebraic function. As with the some of the algebraic mapping approaches described earlier, users can assign a ‘relative importance’ to each attribute map layer. These can then be used to score locations according to their various properties. What is distinctive from the more straightforward overlay mapping methods, however, is that multi-criteria often go further and apply a set of decision rules based on the criteria; as a result the rationale for the outcome for any one point can be traced back through the underlying decision logic to the data that underpinned the analysis. Such methods are typically applied to land allocation problems, and are therefore especially interesting to those wishing to identify opportunities for managing ecosystem services sustainably.

The study by Tenerelli and Carver (2012) on the potential for growing perennial energy crops in Yorkshire, illustrate some of the key features of multi-criteria mapping methods. These workers developed a land suitability model to assess the opportunities associated with the different typologies of perennial crops on the basis of different soil and topographic influences in the area. Following an analysis of the uncertainties associated with the input data and model assumptions, a land allocation algorithm was developed that identified the opportunities for energy crop conversion area given various environmental constraints, such as targets for nature protection, food production priorities and land capability values (Figure 2). Although these practitioners emphasise the preliminary nature of the work, they found that the analysis suggested that the opportunities for expanding energy crops was fairly restricted. They concluded that more than half of the conversion area should be allocated to cropping systems with low land degradation potential, such as short rotation coppice with a growing cycle of more than five years or short rotation forestry.

The multi-objective approaches also usually depend on a set of decision rules, but go further in a sense that they seek to find an optimal solution using a mathematical programming approach. Thus in the context of land allocation, for example they can be used to find the most efficient or most cost-effective spatial pattern of land use given the relationships between decision variables and the problem constraints. By varying the decision criteria a series of alternative planning scenarios can be generated that can be used in decision support role. While the number of approaches that have been used are too numerous to review in detail here, their general character can also be illustrated by an example. When dealing with the problems of land allocation for energy Lautenbach *et al* (2013) note that in the context of polices for biofuel production there are many trade-offs that need to be considered. These arise as a result of different objectives for food and fodder production, goals for water quantity and quality and biodiversity. Using data from the Parthe catchment in Central Germany, they apply a multi-objective genetic algorithm to allocate land between different uses via a set of crop rotations, so as to maximize harvested yield of food crops, maximize harvested yield for bioenergy plants, maximize discharge under low flow conditions, and minimize the average NO_3 concentration. The results illustrate the use of these methods for a kind of opportunity mapping in the sense that the results showed that the same level of bioenergy crop production could be achieved at different costs with respect to the other objectives. They argued that for the study area, intermediate levels of the energy crop rapeseed, does not lead to significant trade-offs with water quality and low flow, if a reduction of food and fodder production can be accepted.

Despite their greater sophistication multi-criteria methods also have limitations. As Malczewski (2004) points out, multi-attribute evaluation procedures, like overlay methods, usually suffer from inaccuracy, imprecision, and ambiguity. Standardising scores across different types of input variable may also lead to difficulties of interpretation. Finally, it is often apparent that different methods applied to the same data may lead to different results. All these problems also apply to multi-objective approaches, which also suffer from issues arising from their complexity. The computational and programming requirements of multi-objective optimisation methods often mean that it is difficult to build them into, and integrate them with, other GIS tools, and as a result the time needed to implement them increases. Although GIS systems often now include multi-criteria tools, the general criticism of such methods that Malczewski (2004) identified in the context of the types of suitability mapping that we are considering here is that, despite their sophistication, they do not generate output allocation patterns that have the properties of congruity and compactness. When assessing what the ‘real opportunities’ are, the neighbourhood relationships between land parcels is often an important factor that needs to be considered, and such criteria are often difficult to include in multi-criteria mapping methods.

2.3 Artificial intelligence methods

Mapping based on Artificial Intelligence (AI) methods are amongst the most novel that are available. It is claimed that they are particularly appropriate when dealing with complex problems that involve using exploratory methods, because they attempt to mimic the kinds of problem solving approaches used by people. According to Malczewski (2004) the key characteristic of these methods is that, compared to the others reviewed here, they are ‘tolerant of imprecision, ambiguity, uncertainty, and partial truth’.

Fuzzy logic and Bayesian Methods illustrate some of the features of the broad group of AI methods. In order to address the limitation that conventional Boolean algebra is over-precise or 'too crisp' given the nature of environmental data and the uncertainties associated with them, 'fuzzy logic' seeks to extend the approach by allowing partial or probabilistic membership to particular classes or sets. Bayesian methods do a similar thing (see Haines-Young, 2011). As a result, mapping of opportunities for the delivery of ecosystem services or the benefits associated with them can be made using some kind of likelihood or probabilistic score. Both methods depend on designing membership functions or rules in order to assign the variable states to classes, and insofar as these rules or functions are often derived from previous experience or the elicitation of expert knowledge they can be regarded as being within the family of AI techniques. Several papers have been recently published on the use of Bayesian methods for making valuations of ecosystem services (e.g. Barton *et al* 2012; McCann *et al* 2006). These methods are now actively being explored as part of this project (See Haines-Young and Potschin, 2013).

The use of fuzzy logic and especially Bayesian methods is now fairly common-place in the ecosystem services literature. The ARIES[4] (ARtificial Intelligence for Ecosystem Services) system, for example, specifically highlights the use of Bayesian methods in its construction, because they are able to communicate uncertainty about inputs to outputs and are suited for use in 'data-scarce conditions where deterministic models cannot run'. The ARIES toolkit provides models that can be either parameterised by the user or automatically trained to extract the quantitative relationships between their inputs using machine learning techniques.

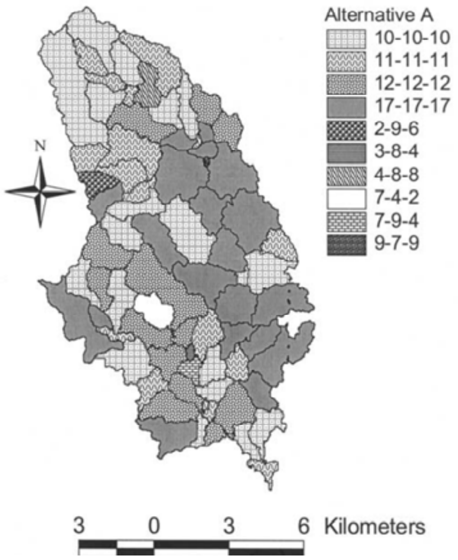
Machine learning is another important feature of AI methods. Network procedures, for example, seek to simulate the way human brains work, by using training data to calibrate the system. The network is trained by providing it with many examples of how the input and output variables are associated. The system stores these relationships as a pattern of inferred connections between the data layers, and these can be applied to a new case or situation. Such systems are adaptive, in the sense that while they can come to an initial approximate solution to a problem, they have the potential to improve their performance by using experience to learn how to do it better. As the user documentation for the ARIES system notes[5], it is capable of using a variety of approaches for the economic valuation of ecosystem services. In addition to multi-criteria approaches, the system can estimate economic values for specific benefits into a 'valuation portfolio' for a user, using aggregated data retrieved from a database using a neural network classification algorithm. The latter identifies most likely ecosystem services given the ecological and economic characteristics of the source and destination areas.

Mapping methods based on evolutionary (genetic) algorithms are also 'adaptive' in the sense that they are designed to search for a solution from a (usually large) population of solutions. Rather than seeking an optimal solution from the outset, evolutionary algorithms are used to compare alternative and eliminate what are judged to be poor solutions. The algorithms are also capable of recombination and mutation procedures to generate new solutions that are biased towards those regions of the solution space for which good outcomes have already been discovered. An application of these kinds of methods is illustrated by the work of Bekele and Nicklow (2005) who applied them to the problem of designing multi-objective management strategies for ecosystem services at the catchment scale in southern Illinois. The analysis integrates the Soil and Water Assessment Tool (SWAT) watershed model with the SPEA2 evolutionary algorithm. The aim was to assess the role of agricultural landscapes in generating improved ecosystem services through a reduction in non-point source pollution while maximizing gross margin achieved in those

[4] http://www.ariesonline.org/docs/ARIESModelingGuide1.0.pdf; see also https://learning.conservation.org/SouthAmericaEcosystemServices/Documents/ES%20Articles%20and%20Documents/2009%20Villa%20et%20al.%20ARIES%20-%20BioEcon%202009.pdf

[5] http://www.ariesonline.org/about/approach.html

landscapes; the work also sought to identify any solutions involving trade-offs. The resulting mapping (Figure 3) shows the alternative management solutions for each catchment in the study area that optimises the output of the selected ecosystem services for the given set of constraints.



Integer Code	Land Use and Tillage Practice Combinations	Acronym
1	soy bean with no tillage	SYNT
2	soy bean with conservation tillage	SYCT
3	soy bean with conventional tillage	SYST
4	corn with no tillage	CRNT
5	corn with conservation tillage	CRCT
6	corn with conventional tillage	CRST
7	sorghum with no tillage	SGNT
8	sorghum with conservation tillage	SGCT
9	sorghum with conventional tillage	SGST
10	hay with no tillage	HYNT
11	pasture with no tillage	PSNT
12	tall fescue grass with no tillage	CRPG

Figure 2. Watershed-level decision alternatives with best ecosystem service outcomes for the combinations of land use and tillage types (after Bekele and Nicklow, 2005).

The final mapping method considered is cellular automata, which is a technique widely used to model where the spatial dynamics are important. The state of the world is represented by a lattice, and the states of the cells that make it up are determined by either probabilistic or deterministic rules that partly depend on their local characteristics (as represented by the states of the surrounding cells and the previous states that it has experienced). All of the cells are updated synchronously, and the system changes in a series of discrete time steps. These methods have traditionally been used to model land -use change using raster data, where the probability of a given transition in a pixel is dependent on the states of its neighbours. However, more sophisticated ‘agent-based’ algorithms are available that enable the spatial unit to behave in ‘intelligent’ or ‘purposive’ ways. Thus agent-based models can be used to represent the responses of, say, land managers or communities as conditions change. Although such systems appear to hold great promise, they suffer the same kind of limitations as the other AI methods, in that they are often computationally resource intensive. Although they can be rich in the theoretical insights they offer, more expertise is needed both to develop and use them in a decision support role. Agent-based methods are used in ARIES to model the flows of ecosystem services across landscapes. A review of agent-based approaches to land cover/use modelling is provided by Matthews *et al* (2007). More recently Valbuena *et al* (2010) have illustrated their use for modelling changes in land management and their impact on ecosystem services in the Netherlands. The study used a typology of different ownership types to represent land managers, each with different propensities to act in certain ways, say in terms of diversification of farm operations, cease farming, or participate in various management programmes. The model was driven by a series of external factors relating to the biophysical and socioeconomic context, and the mapping generated showed how land management strategies (with their resulting consequences) varied across the study area. For example, mapped outputs included the percentage and average numbers of agents (farms) that are likely to participate in a policy to protect linear landscape features (Figure 4).

As a suite of potential mapping methods, AI clearly has the advantage that they can begin to capture both the complexity and uncertainties associated with the 'real world'. Their disadvantage is that they are resource intensive, and there is a danger that they can be seen by decision makers as a 'black box'. Loss of transparency in term of the assumptions underpinning the methods may be one thing that is sacrificed in seeking to more fully represent things as they are on the ground.

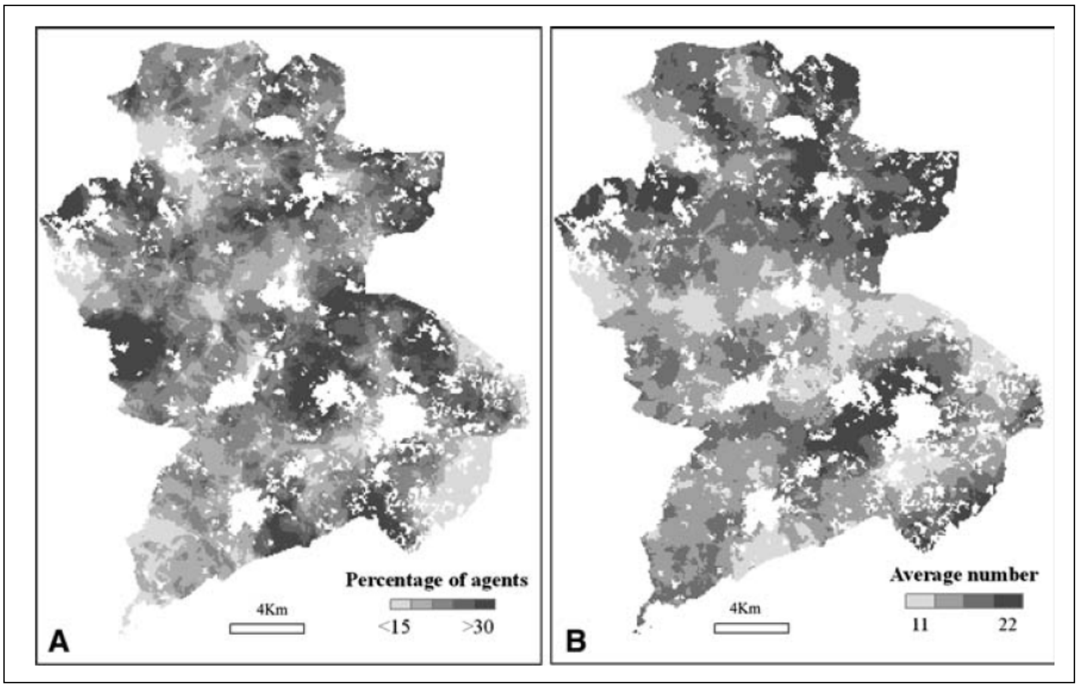


Figure 3. Mapped output from the study of Valbuena et al (2010), showing uptake to protect linear landscape features in the Netherlands

2.4 Participatory methods

Participatory mapping methods are increasingly being reported in the ecosystem service literature. Their 'popularity' partly reflects the belief that stakeholder involvement in making management decisions is essential if they are to be effective, and also that consultation is fundamentally part of 'good governance' as represented by the Ecosystem Approach. Participatory methods are also useful when dealing with complex situations that are not amenable to solutions based on modelling approaches. As the review recently provided by the UK NEA Follow-on has suggested[6], these techniques can be helpful in identifying relationships across landscapes and between stakeholder groups and as a result, provide a 'common understanding of different perspectives, interdependencies and of potentially more mutually-beneficial management'.

Mapping methods usually depend on some kind of knowledge elicitation with stakeholders. This can be done by informal methods involving walking the land with the people who use or manage it, to using base maps to capture locations with particular characteristics that people value. All these methods are based on the assumption that 'local' or 'lay knowledge' is an essential source of information when seeking to understand how and where ecosystem services are generated, and the kinds of benefit that people derive from them. It has been argued that the importance of stakeholder-driven place-based service analysis is likely to grow (cf. Potschin and Haines-Young, 2013).

[6] http://www.eatme-tree.org.uk/pdfs/participatory_mapping_tool_review.pdf

There are many examples of participatory GIS methods being used to tackle problems linked to ecosystem services. A recent study of projects in England where stakeholders were seeking to use the Ecosystem Approach to their decision making (Haines-Young and Potschin, in press) identified participatory mapping as and especially important tool. In one of the case studies considered, which was concerned with designing Payments for Ecosystem Service schemes for improving water quantity and quality in SW England, mapping was used to identify ‘zones of potential agreement’ between stakeholders. In the case study the mapping was created with stakeholder involvement and used to establish ‘best-estimates’ for the costs and benefits of providing ecosystem services. Haines-Young and Potschin (in press) report how in a second case study mapping the locations in the marine space used by different stakeholder groups enabled them to work together to make recommendations for the design of a set of Marine Conservation Zones in the seas around south-west England, as part of a wider network of Marine Protected Areas (MPAs). Other examples include the work of Raymond *et al* (2009) on mapping community values for natural capital and ecosystem services in the South Australian Murray–Darling Basin region. The work involved formal interviews with a number of natural resource management decision-makers and community representatives, to identify what they considered to be the values and threats to natural capital assets and ecosystem services in the study area. Using this information, maps of spatial distribution of natural capital and ecosystem service values were generated by means of overlay and map algebra techniques.

This latter example illustrates one of the problems of any classification of mapping methods, in that all of those described here can probably be used in combination. Whatever mapping technique is used, in the future some element of participatory engagement is, for example, likely to be required if people are to have confidence or to ‘buy-in’ to the results.

2.4.1 Case studies

As noted in the introduction to this briefing note, the terms ‘opportunity’ and ‘benefit mapping’ are fairly loose ones, and can be regarded as part of a broader set of ecosystems service mapping methods. In order to explore the ways in which the concepts have been used by researchers, a search of the relevant literature was made using Scopus. Using the terms “mapping” and “ecosystem service” together around 300 articles and reviews were identified. Given that it is not possible within the scope of this study to review them in detail, a refined search was made to select only those that used the terms ‘opportunity map’ or ‘benefit map’. By restricting the set to those papers which have been peer-reviewed, the number was reduced to around 70. A review of the abstracts of the subset was made and those obviously not relevant were eliminated. Table 1 lists those which appeared to be of greatest interest given the nature of this study. In this table we summarise the key aims of the paper based on the abstract, and note from the material considered whether the paper was concerned with opportunity or benefit mapping. Where possible we also highlighted whether the approach used could broadly be described as involving the use of a production function of some kind, or whether benefit transfer was highlighted. Finally notes were added to flag up if any of the methods reviewed in Part 2 of this report were used.

Table 1. Illustrative Studies involving Opportunity and/or Benefit Mapping Methods.

Key: OP- Opportunity mapping, BM- Benefit mapping, PF- Production function, BT- Benefit Transfer

No	Reference	Abstract	OM	BM	PF	BT	Notes
1.	ALLAN, J.D. *et al* 2013. Joint analysis of stressors and ecosystem services to enhance restoration effectiveness. *Proceedings of the National Academy of Sciences of the United States of America,* **110(1)**: 372-377.	Results demonstrate that joint spatial analysis of stressors and ecosystem services can provide a critical foundation for maximizing social and ecological benefits from restoration investments.	x	x	x		
2.	AYANU, Y.Z. *et al* 2012., Quantifying and mapping ecosystem services supplies and demands: A review of remote sensing applications. *Environmental Science and Technology*, **46(16)**: 8529-8541.	Reviews relevant remote sensing systems, sensor types, and methods applicable in quantifying selected provisioning and regulatory services.	x		x		
3.	BASTIAN, O. *et al* 2013. The five pillar EPPS framework for quantifying, mapping and managing ecosystem services. *Ecosystem Services*, **4**: 15-24.	This paper introduces an ecosystem services assessment framework with five pillars: ecosystem properties, potentials, services, benefits/values, and beneficiaries. In a case study in the district of Görlitz (Eastern Saxony, Germany), we present an exemplary application for two ecosystem services: crop food production and soil erosion regulation.	x	x	x		
4.	BERBÉS-BLÁZQUEZ, M. 2012. A participatory assessment of ecosystem services and human wellbeing in rural Costa Rica using photo-voice. *Environmental management*, **49(4)**: 862-875.	Argues for the need to include of community perspectives in ecosystem assessments in order to better understand the distribution of impacts and benefits resulting from natural resource use		x			Uses participatory methods

No	Reference	Abstract	OM	BM	PF	BT	Notes
5.	BOYKIN, K.G. *et al* 2012. A national approach for mapping and quantifying habitat-based biodiversity metrics across multiple spatial scales. *Ecological Indicators*.	This study notes that wildlife habitat has been modelled at broad spatial scales and can be used to map a number of biodiversity metrics and presents an approach that (1) identifies mappable biodiversity metrics that are related to ecosystem services or other stakeholder concerns, (2) maps these metrics throughout a large multi-state region, and (3) compares the metric values obtained for selected watersheds within the regional context.	x		x		
6.	BRYAN, B.A. *et al* 2013. Ecohydrological and socioeconomic integration for the operational management of environmental flows. *Ecological Applications*, **23(5)**: 999-1016.	Considers how investment in and operation of flow control infrastructure such as dams, weirs, and regulators can help increase both the health of regulated river ecosystems and the social values derived from them.	X	X	X		Uses multi-criteria, optimization methods
7.	CAI, J., YIN, H. & HUANG, Y. 2010. Ecological function regionalization: A review. *Shengtai Xuebao/ Acta Ecologica Sinica,* 30(11): 3018-3027.	Considers the concept of Ecological Function Regionalization (EFR) to support ecosystem management and sustainable development. Presents a method for classifying and mapping ecological units at the regional scale, based on integrating the information of the nature and distribution of ecosystems, as well as ecological patterns and processes and the interrelationships among social, physical, and biological systems.	x		x		
8.	CAMACHO-VALDEZ, V. *et al* 2013. Valuation of ecosystem services provided by coastal wetlands in northwest Mexico. *Ocean and Coastal Management*, **78**: 1-11.	This research introduces a spatial component for classifying wetland types and further evaluation of their ecosystem services, assessing their current distribution and extent using standardized remote sensing techniques for wetland mapping. A value transfer approach was performed to generate baseline estimates of the ecosystem services provided by wetlands, validating it through a meta-analysis of a database of wetland estimates, with northwest Mexico wetlands as case study.			x	x	
9.	CASALEGNO, S. *et al* 2013. Spatial Covariance between Aesthetic Value & Other Ecosystem Services. *PLoS ONE*, **8(6)**.	Describes an approach for evaluating a cultural service, based on the perceived aesthetic value of ecosystems as quantified using geo-tagged digital photographs uploaded to social media resources. Considers trade-offs between cultural services and carbon and agricultural production.	x	x	x		

No	Reference	Abstract	OM	BM	PF	BT	Notes
10.	CIMON-MORIN, J., DARVEAU, M. & POULIN, M. 2013. Fostering synergies between ecosystem services and biodiversity in conservation planning: A review. *Biological Conservation*, **166**: 144-154.	Examines how the most effective approach to identifying ES priority areas for conservation is based on quantifiable biophysical indicators as well as their spatiotemporal flow scale. Authors found a general lack of spatial congruence between biodiversity and ES is attributable to: (i) the type of data used for ES mapping; (ii) the greater accuracy of functional diversity, compared to other biodiversity features, in predicting ES provision; (iii) the higher positive spatial correlation of regulating services with biodiversity, whereas provisioning services are negatively correlated.					A review paper
11.	DAVIES, Z.G. *et al* 2011. Mapping an urban ecosystem service: Quantifying above-ground carbon storage at a city-wide scale. *Journal of Applied Ecologyi,* **48(5)**: 1125-1134.	Illustrates the potential benefits of accounting for, mapping and appropriately managing above-ground vegetation carbon stores, even within a typical densely urbanized European city.	X		x		Case study area is the city of Leicester.
12.	DUNN, R.R. 2010. Global Mapping of Ecosystem Disservices: The Unspoken Reality that Nature Sometimes Kills us. *Biotropica*, **42(5)**: 555-557.	Consider what we know about the spatial pattern of the disservice represented by pathogen prevalence and how changes in habitat influence it.	x		x		
13.	EIGENBROD, F. *et al* 2010. Error propagation associated with benefits transfer-based mapping of ecosystem services. *Biological Conservation*, **143(11)**: 2487-2493.	Consideres and analyses the errors that may arise in benefit transfer methods due to the limitations of available spatial data.		X		X	Provides methodolgoical support

No	Reference	Abstract	OM	BM	PF	BT	Notes
14.	ERICKSEN, P. *et al* 2012. Mapping ecosystem services in the Ewaso Ng'iro catchment. *International Journal of Biodiversity Science*, *Ecosystems Services and Management,* **8(1-2)**: 122-134.	Describes an exercise to portray, quantify and map bundles of ecosystem services in the arid and semi-arid lands of northern Kenya. To construct maps of ecosystem services, the study delineated and described the natural resource base, as well as the physical and human geography and physical infrastructure of the catchment.	X		X		
15.	FAGERHOLM, N. *et al* 2012. Community stakeholders' knowledge in landscape assessments - Mapping indicators for landscape services. *Ecological Indicators*, **18**: 421-433.	Uses a typology of 19 different material and non-material, cultural landscape service indicators which are then mapped using information derived from semi-structured interviews; the method allows community stakeholders to map these indicators individually on an aerial image.	X	X			Participatory methods
16.	FOLEY, D.H. *et al* 2012. Sandflymap: Leveraging spatial data on sand fly vector distribution for disease risk assessments. *Geospatial Health.* **6(3 SUPPL.)**: S25-S30.	Case study dealing with disease risk.	X		X		
17.	FU, B. *et al* 2013. Mapping the flood mitigation services of ecosystems - A case study in the Upper Yangtze River Basin. *Ecological Engineering*, **52**: 238-246.	Illustrates a production function approach that could be used to identify high-value areas for ecological protection and also to provide information for decision-making related to integrated flood management.	X	X	X		
18.	GHERMANDI, A., DING, H. & NUNES, P.A.L.D. 2013. The social dimension of biodiversity policy in the European Union: Valuing the benefits to vulnerable communities. *Environmental Science and Policy*, **33**: 196-208.	This paper uses GIS-based mapping tools and economic valuation of ecosystem goods and services to explore the social dimension of biodiversity policy.	X	X	X		

No	Reference	Abstract	OM	BM	PF	BT	Notes
19.	GOLDSTEIN, J.H. *et al* 2012. Integrating ecosystem-service tradeoffs into land-use decisions. *Proceedings of the National Academy of Sciences of the United States of America*. **109(19)**: 7565-7570.	Uses the InVEST software tool to evaluate the environmental and financial implications of seven planning scenarios encompassing contrasting land-use combinations including biofuel feedstocks, food crops, forestry, livestock, and residential development.		X	X		
20.	HAMEL, M.A. & ANDRÉFOUËT, S. 2010. Using very high resolution remote sensing for the management of coral reef fisheries: Review and perspectives. *Marine Pollution Bulletin*, **60(9)**: 1397-1405.	The paper argues that availability of habitats maps improves management by guiding sampling strategies, mapping resources, involving local communities, identifying conservation areas, and facilitating Ecosystem Based Fishery Management (EBFM) approaches. Examines the contribution of high resolution remote sensing as a data source for these maps.	X		X		
21.	HAUCK, J. *et al* 2013. "Maps have an air of authority": Potential benefits and challenges of ecosystem service maps at different levels of decision making. *Ecosystem Services*, **4**: 25-32.	This paper presents results drawn from interviews on a regional level and from a focus group discussion on national and EU levels. The aim was to understand how spatially explicit information was used in decision-making concerning biodiversity and ecosystem services.					Provides insights into design of OM and BM.
22.	HERNÁNDEZ-MORCILLO, M., PLIENINGER, T., & BIELING, C. 2013. An empirical review of cultural ecosystem service indicators. *Ecological Indicators*, **29**: 434-444.	Reviews frameworks for developing a holistic understanding of how cultural services indicators are conceived within ecosystem services research.					

No	Reference	Abstract	OM	BM	PF	BT	Notes
23.	HEUBES, J. *et al* 2012. Impact of Future Climate and Land Use Change on Non-timber Forest Product Provision in Benin*, West Africa: Linking Niche-based Modeling with Ecosystem Service Values*, **66(4)**: 383-397.	Describes the quantification and monetary mapping of important Non-timber Forest Products (NTFPs) and the development of a novel approach to assess the impacts of climate and land use change on the economic benefits derived from these NTFPs.		X	X		
24.	ISELY, E.S. *et al* 2010. Addressing the information gaps associated with valuing green infrastructure in west Michigan: INtegrated Valuation of Ecosystem Services Tool (INVEST). *Journal of Great Lakes Research*, **36(3)**: 448-457.	Uses InVEST tool and its ability to use static GIS maps, graphs, and tables, to help educate local and regional decision-makers about the underlying values of ecosystem services associated with green infrastructure, particularly those services that do not pass through traditional commercial markets.		X	X	X	
25.	JACKSON, B. *et al* 2013. Polyscape: A GIS mapping framework providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services. *Landscape and Urban Planning*, **112(1)**: 74-88.	Describes Polyscape System funcitonality.	X	X	X		Technical overview, focus on overlay and multi-criteria methods.
26.	JIANG, M., BULLOCK, J.M., & HOOFTMAN, D.A.P. 2013. Mapping ecosystem service and biodiversity changes over 70 years in a rural English county. *Journal of Applied Ecology*, **50(4)**: 841-850.	Maps association between land use changes and biodiversity changes and assocated ecosystem service outputs.	X		X		Historical analysis

No	Reference	Abstract	OM	BM	PF	BT	Notes
27.	JONES, K.B. *et al* 2012. Informing landscape planning and design for sustaining ecosystem services from existing spatial patterns and knowledge. *Landscape Ecology*, 1-18.	Reviews ways to improve understanding of how landscape pattern influences ecosystem services, by: (1) characterizing and mapping landscape pattern gradients; (2) quantifying relationships between landscape patterns and environmental targets and ecosystem services, (3) evaluating landscape patterns with regards to multiple ecosystem services, and (4) applying adaptive management concepts to improve the effectiveness of specific landscape designs in sustaining ecosystem services.	X	X	X		
28.	KLAIN, S.C. & CHAN, K.M.A. 2012. Navigating coastal values: Participatory mapping of ecosystem services for spatial planning. *Ecological Economics*, **82**: 104-113.	The study examined whether maps and semi-structured interviews-enabled and/or impeded the elicitation of intangible ecosystem service values, and sought to identify what categories of ecosystem benefits do participants identify as most important. Explored whether the spatial distributions of monetary values correlated with non-monetary values and threats.	X	X	X		Participatory mapping methods
29.	KOSCHKE, L. *et al* 2013. The integration of crop rotation and tillage practices in the assessment of ecosystem services provision at the regional scale. *Ecological Indicators*, **32**: 157-171.	The focus of this research was on an indicator-based approach to assess ecosystem services and the development of land use change (LUC) and land management change (LMC) scenarios.	X		X		
30.	LAKES, T. & KIM, H.O. 2012. The urban environmental indicator "biotope Area Ratio" - An enhanced approach to assess and manage the urban ecosystem services using high resolution remote-sensing. *Ecological Indicators*, **13(1)**: 93-103.	Seeks to develop a method based on 'Biotope Area Ratios' to assess and value ecosystem services in urban areas and integrate them in urban decision-making processes; considers high resolution remotely sensed data as a potential information source.	X		X		

No	Reference	Abstract	OM	BM	PF	BT	Notes
31.	LAVOREL, S. *et al* 2011. Using plant functional traits to understand the landscape distribution of multiple ecosystem services. *Journal of Ecology*, **99(1)**: 135-147.	The paper proposes a new approach for the analysis, mapping and understanding of multiple ES delivery in landscapes. It uses spatially explicit single ES models based on plant traits and abiotic characteristics, which are combined to identify 'hot' and 'cold' spots of multiple ES delivery, and the land use and biotic determinants of such distributions.	X		X		
32.	LIQUETE, C. *et al* 2011. Securing water as a resource for society: An ecosystem services perspective. *Ecohydrology and Hydrobiology*, **11(3-4)**: 247-259.	This study presents a spatially explicit assessment of the benefits of water services at the European scale. It maps simple indicators for water provision, water regulation by soils, and water purification by river networks. Both the capacity to provide services as well as the actual flow of services are quantified in biophysical terms.	X				
33.	LIQUETE, C. *et al* 2013. Current Status and Future Prospects for the Assessment of Marine and Coastal Ecosystem Services: A Systematic Review. *PLoS ONE*, **8(7)**.	This review summarizes the state of available information related to ecosystem services associated with marine and coastal ecosystems.					Review of methods
34.	LIQUETE, C. *et al,*2013. Assessment of coastal protection as an ecosystem service in Europe. *Ecological Indicators*, **30**: 205-217.	This paper provides a conceptual and methodological approach to assess coastal protection as an ecosystem service at different spatial-temporal scales, and applies it to the entire EU coastal zone; it is based on the 14 biophysical and socio-economic variables from both terrestrial and marine datasets.	X	X	X		
35.	MAES, J. *et al* 2013. Mainstreaming ecosystem services into EU policy. *Current Opinion in Environmental Sustainability*, **5(1)**: 128-134.	Presents multi-scale mapping and assessment approach of ecosystem services using three case studies across Europe.	X		X		Provides insight into early work done within the MAES initative.

No	Reference	Abstract	OM	BM	PF	BT	Notes
36.	MEHAFFEY, M. *et al* 2011. Developing a dataset to assess ecosystem services in the Midwest United States. *International Journal of Geographical Information Science*, **25(4)**: 681-695.	This article describes a procedure for developing a dataset containing multiple variables useful in modelling ecological responses and tradeoffs. It demonstrates how to construct a detailed land cover classification and link it to yield and agricultural practices.	X		X		
37.	NAHUELHUAL, L. *et al* 2013. Mapping recreation and ecotourism as a cultural ecosystem service: An application at the local level in Southern Chile. *Applied Geography*, **40**: 71-82.	This study proposes a methodological framework that combines GIS and participatory methods (Delphi method and Analytic Hierarchy Process) to map recreation and ecotourism at the municipality level.	X	X	X		Uses particpatory methods
38.	NAIDOO, R. *et al* 2008. Global mapping of ecosystem services and conservation priorities. *Proceedings of the National Academy of Sciences of the United States of America*, **105(28)**: 9495-9500.	A global study that uses available data to compare ecosystem service maps with the global distributions of conventional targets for biodiversity conservation. Results show that regions selected to maximize biodiversity provide no more ecosystem services than regions chosen randomly.	X		X		
39.	NAIDOO, R. & RICKETTS, T.H. 2006. Mapping the economic costs and benefits of conservation. *PLoS Biology*, **4(11)**: 2153-2164.	The paper describes work on making a spatial evaluation of the costs and benefits of conservation for a landscape in the Atlantic forests of Paraguay. The services considered were sustainable bushmeat harvest, sustainable timber harvest, bioprospecting for pharmaceutical products, existence value, and carbon storage in above ground biomass. The assessments for these services were compared to estimates of the opportunity costs of conservation.	X	X	X		
40.	NEDKOV, S. & BURKHARD, B. 2012. Flood regulating ecosystem services - Mapping supply and demand, in the Etropole municipality, Bulgaria. *Ecological Indicators*, **21**: 67-79.	The paper shows that the combination of data from different sources with hydrological modelling provides a suitable data base for the assessment of complex function-service-benefit relations.	X	X	X		

No	Reference	Abstract	OM	BM	PF	BT	Notes
41.	NEWTON, A.C. *et al* 2012. Cost-benefit analysis of ecological networks assessed through spatial analysis *of ecosystem services. Journal of Applied Ecology*, **49(3)**: 571-580.	Examines the potential impact of landscape-scale habitat restoration on the value of multiple ecosystem services across the catchment of the River Frome in Dorset, England.	X	X	X		Uses mult-criteria assessment methods
42.	PALOMO, I. *et al* 2013. National Parks, buffer zones and surrounding lands: Mapping ecosystem service flows. *Ecosystem Services*, **4**: 104-116.	Uses expert workshops and participatory mapping techniques to map services associated with the protected areas of Doñana and Sierra Nevada in Spain.	X	X			Participatory methods
43.	PFEIFER, C., SONNEVELD, M.P.W., & STOORVOGEL, J.J. 2012. Farmers' contribution to landscape services in the Netherlands under different rural development scenarios. *Journal of Environmental Management*, **111**: 96-105.	Study mapped the spatial distribution of the adoption of on-farm rural activities under different explorative scenarios.	X	X	X		
44.	PLIENINGER, T. *et al* 2013. Assessing, mapping, and quantifying cultural ecosystem services at community level. *Land Use Policy*, **33**: 118-129.	This study performs a spatially explicit participatory mapping of the complete range of cultural ecosystem services and several disservices perceived by people living in a cultural landscape in Eastern Germany.	X	X	X		
45.	RICKETTS, T.H. & LONSDORF, E. 2013. Mapping the margin: Comparing marginal values of tropical forest remnants for pollination services. *Ecological Applications*, **23(5)**: 1113-1123.	Describes an approach to mapping marginal values that arise in relation to land use change across landscapes for crop pollination services in Costa Rica. Simulations of deforestation events were used to predict resulting marginal changes in pollination services to coffee farms.	X	X	X		

No	Reference	Abstract	OM	BM	PF	BT	Notes
46.	ROMÁN, M.V., D. AZQUETA, & RODRÍGUES, M. 2013. Methodological approach to assess the socio-economic vulnerability to wildfires in Spain. *Forest Ecology and Management*, **294**: 158-165.	This study aimed to develop a methodology for the assessment of the socio-economic vulnerability to fire using Geographic Information Systems, based on an analysis of that vegetation recovery time. The latter depends on the vegetation's structure, the reproductive strategy and the influence of constraining factors such as water availability, soil loss, fire frequency and fire intensity.	X	X	X		
47.	SCHAAFSMA, M. *et al* 2012. Towards transferable functions for extraction of Non-timber Forest Products: A case study on charcoal production in Tanzania. *Ecological Economics*, **80**: 48-62.	The paper argues that mapping the distribution of the quantity and value of forest benefits to local communities is useful for forest management, when socio-economic and conservation objectives may need to be traded off. It develop a modelling approach for the economic valuation of annual Non-Timber Forest Product (NTFP)	X	X	X		
48.	SILVESTRI, S. *et al* 2013. Valuing ecosystem services for conservation and development purposes: A case study from Kenya. *Environmental Science and Policy*, **31**: 23-33.	This paper makes an analysis of the spatial distribution of resources and the existing competition over these resources, alongside the current values attributed to the selected ecosystem services. By mapping existing supporting infrastructure and drivers of land use change such as demographic pressure, the paper highlight trade-offs and synergies among alternative uses and opportunities for sustainable development in Kenya.	X	X	X		
49.	SUTTON, P.C. *et al* 2012. The real wealth of nations: Mapping and monetizing the human ecological footprint. *Ecological Indicators*, **16**: 11-22.	A global study that seeks to assess the 'costs' and 'benefits' using proxy measures for ecosystem services and their drivers, and derive a total value of the world's ecosystem services based on the total cost of anthropogenic environmental impacts	X	X	X		
50.	TERMANSEN, M., McCLEAN, C.J., & JENSEN, F.S. 2013. Modelling and mapping spatial heterogeneity in forest recreation services. *Ecological Economics*, **92**: 48-57.	This paper combines recreational choice modelling and economic valuation with GIS based techniques to allow an assessment of the spatial diversity of the value of forest recreation services.	X	X	X		

No	Reference	Abstract	OM	BM	PF	BT	Notes
51.	TROY, A. & WILSON, M.A. 2006. Mapping ecosystem services: Practical challenges and opportunities in linking GIS and value transfer. *Ecological Economics*, **60(2)**: 435-449.	This paper describes a decision framework designed for spatially explicit value transfer was used to estimate ecosystem service flow values and to map results for three case studies in North America.	X	X		X	
52.	UY, N. & SHAW, R. 2013. Ecosystem resilience and community values: Implications to ecosystem-based adaptation. *Journal of Disaster Research*, **8(1)**: 201-202.	By assessing the resilience of ecosystems and mapping of community values and actions, this study shows potential 'entry points' for an ecosystem-based adaptation strategy are identified while addressing positive and negative factors as well as gaps and opportunities to enhance the resilience of Infanta's ecosystems.		X			Participatory methods
53.	VADREVU, K.P. *et al* 2008. Case study of an integrated framework for quantifying agroecosystem health. *Ecosystems*, **11(2)**: 283-306.	This study described and analysed a method to quantify agroecosystem health through a combination of geographically referenced data at various spatial scales. Six key variables were hypothesized to provide a minimum set of conditions required to quantify agroecosystem health: soil health, biodiversity, topography, farm economics, land economics, and social organization.	X	X	X		
54.	YAPP, G., WALKER, J., & THACKWAY, R. 2012. Linking vegetation type and condition to ecosystem goods and services. *Ecological Complexity*, **7(3)**: 292-301.	The paper uses vegetation types and their condition classes as a first approximation or surrogate to define and map the underlying ecosystems in terms of their regulating, supporting, provisioning and cultural services.	X		X		

A number of features emerge from the preliminary literature review:

- The phrases ‘opportunity-’ and ‘benefit-mapping’ were predominantly used in a descriptive way, to explain what was being done, rather than to reference the study to any well-defined methodology. The situation can be illustrated by a comparison with the term benefit transfer. The latter is a well understood and quite specific term, while benefit mapping merely describes any attempt to describe the spatial pattern in some value arising from an ecosystem service using any method that the researcher feels appropriate. But they are clearly not synonymous: not all benefit transfer studies involve mapping and, not all benefit mapping exercises involve benefit transfer. We therefore suggest that if the terms are used to illustrate the types of application that the database being created can support, they are not used more to illustrate concepts rather than to suggest that particular types of application are being targeted.

- Given the non-specific nature of the terms ‘opportunity-’ and ‘benefit-mapping’, the literature review is probably unrepresentative of the kinds of mapping approach that are being used and the methods employed. A much larger set of studies would have been identified if descriptors of the techniques considered in section 2 were used together with the term ecosystem service. For example, 59 papers were found by looking for the use of the terms ‘multi-criteria’ and ‘ecosystem services’, few of which were found in the search reported in Table 1. Thus if at some later stage this literature review is refined, then probably a better strategy would be to search by method and then select or rate the papers by relevance to issues such as constraint and suitability mapping as well as opportunity and benefit etc.

- Whatever search strategy is used, however, it is apparent that there is no simple way to categorise papers because people mix and match methods. Any database therefore created from the review of relevant literature would have to be indexed using a number of different key words if it were to be useful. The review material should also be clearly differentiated between papers which merely illustrate a method, from other which review and develop particular methodological techniques.

3 Conclusions and next steps

Given that the notions of opportunity- and benefit-mapping are rather open-ended concepts, for this briefing paper we have focussed on the broader mapping methods that have been used to undertake this kind of work. In the context of the present study, and especially in terms of looking at how the *Ecosystem Spatial Framework Database* can be used and developed, it is clear that that conceptually it can most easily support work that seeks to adopt a production function approach, but with refinement it may also assist in benefit-transfer type studies. The identification of habitat, soil and management factors that may influence the output of ecosystem services is clearly the equivalent to specifying how specific data layers can be combined to map spatial variations in service output. However, if that same system can suggest how service output might vary if one of the underlying factors is changed of is different in another location, then it may also support the kind of analysis that is used in benefit transfer studies. The key here would be to ensure that the levels of the factors in the database for a given habitat could be modified by the user and the predicted service output adjusted accordingly by the system.

To do this it would be necessary to ensure that the services covered in the database were described in such a way that the valuations used in the wider literature could be linked to them. By way of exploring how this could be done, in the current study we have developed a prototype BBN that links a range of biophysical characteristics to a subset of ecosystem services (see Medcalf *et al* 2013). While this system can be used to help the user identify which kinds of service might be important in different habitats, it could equally be used as a mapping tool. If each biophysical characteristic is held as a separate layer, for example, or a simple habitat map is used as the input, the BBN could predict the importance of different services. Moreover, if the input layers are modified to reflect a change of management or policy, say, then the *marginal* difference is service output could be estimated as the first step in making an assessment of changes in the value. There is therefore a good prospect of using these methods to map both for identifying opportunities for improved ecosystem service management and the changes in benefit levels associated with these interventions. In order to make use of the growing body of literature on valuation the opportunity and benefit mapping approaches described here should use a standard typology of ecosystem services so that experience and examples gained in one area can be transferred to other places. The use of CICES in the current project will be helpful in this respect, but future work may be needed to understand better how it could be linked to the various valuation databases such as ENVI[7] that are now available. The problem here is that they do not index data by any specific habitat categories, but allow users simply to search for relevant studies using keywords. The habitat translation tools that are currently being developed may help ensure the more systematic use of these kinds of data for the application of benefit transfer methods.

[7] https://www.evri.ca/Global/Home.aspx

4 References

BARTON, D. N. *et al* 2012. Bayesian Networks in Environmental and Resource Management. *Integrated Environmental Assessment and Management*, **8(3)**: 418–429.

BEKELE, E. G. & NICKLOW, J. W. 2005. Multiobjective management of ecosystem services by integrative watershed modeling and evolutionary algorithms. *Water Resources Research*, **41(10)**: W10406-10401-W10406-10410.

BURKHARD, B. *et al* 2012. Mapping ecosystem service supply, demand and budgets. *Ecological Indicators*, **21**: 17-29.

CROSSMAN, N. D. *et al* 2013. A blueprint for mapping and modelling ecosystem services. *Ecosystem Services*, **4**: 4-14.

HAINES-YOUNG, R. 2011. Exploring ecosystem service issues across diverse knowledge domains using Bayesian Belief Networks. *Progress in Physical Geography*, **35(5)**: 681-700.

HAINES-YOUNG, R. & POTSCHIN, M. (in press). The Ecosystem Approach as a framework for understanding knowledge utilisation. *Environment and Planning C*.

HAINES-YOUNG, R., POTSCHIN, M. & KIENAST, F. 2012. Indicators of ecosystem service potential at European scales: Mapping marginal changes and trade-offs. *Ecological Indicators*, **21**: 39-53.

JACKSON, B. *et al* 2013. Polyscape: A GIS mapping framework providing efficient and spatially explicit landscape-scale valuation of multiple ecosystem services. *Landscape and Urban Planning*, **112(1)**: 74-88.

KIENAST, F., BOLLIGER, J., POTSCHIN, M., DE GROOT, R.S., VERBURG, P.H., HELLER, I., WASCHER, D. & HAINES-YOUNG, R.H. 2009. Assessing landscape functions with broad-scale environmental data: insights gained from a prototype development for Europe. *Environmental Management*, **44**: 1099–1120.

LAUTENBACH, S. *et al* 2013. Optimization-based trade-off analysis of biodiesel crop production for managing an agricultural catchment. *Environmental Modelling and Software* **48**: 98-112.

MALCZEWSKI, J. 2004. GIS-based land-use suitability analysis: A critical overview. *Progress in Planning*, **62(1)**: 3-65.

MALCZEWSKI, J. 2006. GIS-based multicriteria decision analysis: A survey of the literature. *International Journal of Geographical Information Science*, **20(7)**: 703-726.

MATTHEWS, R. B. *et al* 2007. Agent-based land-use models: A review of applications. *Landscape Ecology*, **22(10)**: 1447-1459.

McCANN, R. *et al* 2006. Bayesian Belief Networks: applications in natural resource management. Canadian *Journal of Forest Research*, **36**: 3053-3062.

MEDCALF, K.A., SMALL, N., WILLIAMS, J., BLAIR, T., FINCH, C., HAINES-YOUNG, R., POTSCHIN, M. & PARKER, J. 2013. Further development of a spatial framework for mapping ecosystem services. *Report to JNCC*.

POTSCHIN, M. & HAINES-YOUNG, R. 2013. Landscape and the place-based analysis of Ecosystem Services. *Landscape Ecology*, **28**: 1053-1065.

RAYMOND, C. M. *et al* 2009. Mapping community values for natural capital and ecosystem services. *Ecological Economics*, **68(5)**: 1301-1315.

TALLIS, H. & POLASKY, S. 2011b. *How much information do we need? The sensitivity of ecosystem service decisions to model complexity. In*: KARVERA, P., TALLIS H., RICKETTS, T.H., DAILY, G.C. & POLASKY, S. (eds) Natural Capital: Theory and Practice of Mapping Ecosystem Services. Oxford: Oxford University Press, 264–277.

TALLIS, H. & POLASKY, S. 2009. Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. *Annals of the New York Academy of Sciences*, **1162**: 265-283.

TALLIS, H. & POLASKY, S. 2011a. *Assessing multiple ecosystem services: An integrated tool for the real world. In:* KARVERA, P., TALLIS H., RICKETTS, T.H., DAILY, G.C., & POLASKY, S. (eds) Natural Capital: Theory and Practice of Mapping Ecosystem Services. Oxford: Oxford University Press, 34–52.

TENERELLI, P. & CARVER, S. 2012. Multi-criteria, multi-objective and uncertainty analysis for agro-energy spatial modelling. *Applied Geography*, **32(2)**: 724-736.

VALBUENA, D. *et al* 2010. An agent-based approach to model land-use change at a regional scale. *Landscape Ecology*, **25(2)**: 185-199.