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Review

Mapping Agricultural Ecosystem Services across Scales

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Abstract: Given the cross-scale interactions of agricultural ecosystems, it is important to collect ecosystem service data at the multiple spatial scales they operate at. Mapping of ecosystem services helps to assess their spatial and temporal distribution and is a popular communication tool of their availability and value. For example, maps can be used to quantify distance between areas of available ecosystem services and their beneficiaries and how services fluctuate with changes in land use patterns over time, allowing identification of synergies and trade-offs. However, a lack of local context and too large a resolution can reduce the utility of these maps, whilst masking heterogeneities in access due to equity dynamics. This review identifies and summarizes eight main methods of ESS mapping found in the literature – remote sensing, biophysical modelling, agent based modelling, economic valuation, expert opinion, user preference, participatory mapping, and photo-elicitation. We consider what spatial scales these methods are utilized at and the transferability of data created by each method. The analysis concludes with a methodological framework for mapping ecosystem services, intended to help researchers identify appropriate methods for a multi-scale research design. The framework is exemplified with an overview of a research project in Ethiopia.

Keywords: Ecosystem services; agricultural systems; mapping; values; cross-scale; participatory; local.

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1. Introduction

Agricultural ecosystems are social-ecological systems (SES) managed around the production of commodities, whether food or non-food. Given the connectedness of agricultural ecosystems, it is important to examine the multiple spatial scales they operate at, from the field level, to farming landscapes, to examining the sector as a whole. It is also important to acknowledge their connections between social and ecological sub-systems - hence the importance of a focus on ecosystem services (ESS) in these systems. We differentiate between ecosystem functions and ecosystem services. The characteristic exchanges and processes within an ecosystem are its functions, and these include energy and nutrient exchanges, regulation of climate and hydrological cycles, and decomposition and production of biomass [1]. In contrast, ecosystem services are "the set of ecosystem functions that

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are useful to humans" [2] (p. 468), i.e., have an anthropocentric benefit. For example, pollination as an ecosystem function is necessary for ecosystems to sustain over time. In contrast, pollination as an ecosystem service refers to the pollination of food or fuel crops e i.e. those of use to humans. Population growth during the past century has been accompanied by increasing transition of land to agriculture, and this is projected to continue, creating the need to feed an additional 3 billion people from a degraded resource base. In order to adjust to the changing footprint of agriculture, there is an increasing need for both design and management that can monitor the trade-offs using land for agriculture creates whilst improving the triple bottom line - social, environmental and economic - sustainability of agricultural systems [3]. A critical part of designing both policy and field-level management strategies is to ensure the protection of these ecosystem functions that agriculture relies on and thus the supply of ecosystem services to people within agricultural systems and dependent on them. In order to do this we require methods of inquiry that can analyze the dynamic nature of ecosystem functions and services within agricultural systems, including cross-scale dynamics.

Many studies of agricultural ecosystem services are either a part of global ESS assessment i.e. [4,5] or a section in landscape ESS assessment i.e. [6], which may provide crucial information but does not overtly represent the overall agricultural system. Similarly, many studies have focused on ESS provided by protected areas and these areas often exclude agricultural activities [7]. Agricultural ecosystems are unique in themselves and demand to be studied distinctively, as the most directly managed resources required to meet the human necessities, but also given their supplies and demands to other ESS [8,9].

There is a large literature outlining the ecosystem services offered by agricultural systems [2,9–16], from which the Figure 1 is created. What can be seen from Figure 1 is that agricultural ecosystems, by design, offer a wide range of provisioning ESS. Critically, studies such as the Millennium Ecosystem Assessment highlighted that, whilst dependent on regulating and supporting services, they also provide regulating, cultural, and supporting ESS, and that there are trade-offs between managing for provisioning and other categories of ESS [10]. Therefore, assessment methods are necessary that allow comparison of agricultural systems (including both crop-based and animal-based) and trade-offs their management creates.

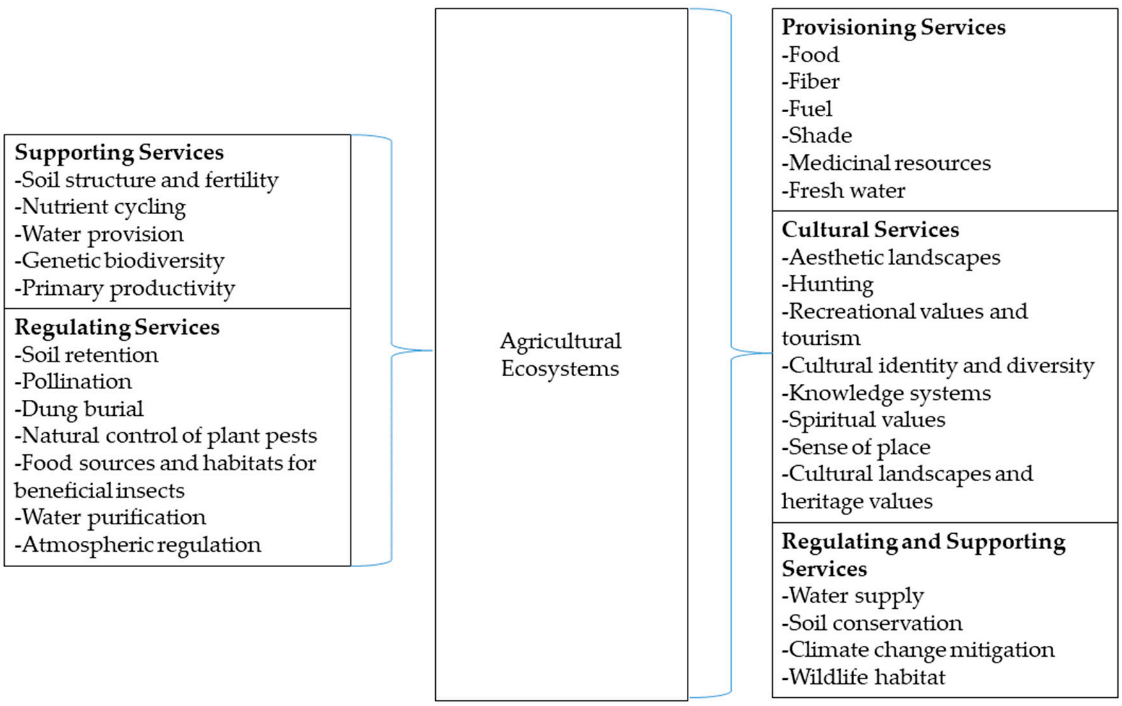

Figure 1. The flow of ecosystem services into and out of agricultural ecosystem services (adapted from [9,16]).

The role of maps in supporting ESS management is noted by multiple researchers [17,18] regarding quantifying ESS in a more holistic way to support agricultural ecosystems. Mapping of ESS in agricultural systems helps to assess their distribution, as both supply and demand of these resources are spatially explicit [19]. For example, maps can be used to quantify and assess the spatial distance between areas of available ecosystem services and their beneficiaries and how ESS correspondingly fluctuate with changes in land use patterns over time [5,17]. Other mapping exercises have been used to identify synergies and trade-offs of ESS, at a range of scales from continental to local, but are limited to 30m resolution or above if utilizing satellite data and have been applied in forest landscapes more than agricultural ones [20–23].

Even with its explosion in popularity, aspects in mapping of ESS are still under development. Mapping initiatives are mostly undertaken above the municipality scale [5,24], with the risk of viewing agricultural ecosystems as a homogenous unit, whereas in reality agricultural ecosystems have both production and conservation goals which require a fine-grained understanding of the ecosystem to capture multiple smaller scale heterogeneity. As a result, there are not comprehensive guidelines for the selection of appropriate ESS mapping methods at smaller spatial scales.

Additionally, prior reviews have found that the majority of studies are based on proxies and secondary data, applied at broad scales, without validation techniques, and map regulating services most commonly, followed by provisioning, cultural, and supporting services [24]. Such reviews end with a call to develop methods that deepening our understanding of the social–ecological processes behind the supply of ESS in order to improve our ability to map ESS for decision making. As such, recent literature has begun to integrate data information with different methods that create data regarding managers' perceptions, improving the understanding of dynamic agricultural ecosystems. These methods include: remote sensing, biophysical modelling, agent based modelling, economic valuation, expert opinion, user preference, participatory mapping, and photo-elicitation. Each of these methods have their own strengths and limitations, outlined below – for example, biophysical modelling requires large quantitative datasets, while user preference data may have lower reproducibility. We conclude with a framework for designing ESS studies that collect mapping data at multiple scales, to create the most detailed study possible for managers to utilize in planning.

2. Materials and Methods

There have been multiple reviews of ecosystem services mapping. Our objective is to build on prior reviews by using them to identify the weaknesses in mapping to date, and then reviewing the literature for methods that addresses these weaknesses. For example, methods that collect primary data 1) at the local scale and 2) on regulating, provisioning, *and* cultural ESS (as per [15], we assume supporting ecosystem services are included within these categories as they underlying their production). We therefore carried out a methodological review [25] with a goal of creating a framework of understanding regarding data collection for ecosystem service mapping across spatial scales.

Firstly, existing review papers were identified by searching peer-reviewed publication databases for review papers that included these criteria: "ecosystem services mapping" + agriculture + review. Google scholar yielded 734 individual peer-reviewed articles for the combination of all three search terms, but few of these publications were review papers, so the dataset was honed by the authors to identify recent (10 years) review papers. Ten review papers were identified and are listed in Table 1. Given that these ten articles were based on the literature review and/or meta-analysis, we assume that they summarize the state of knowledge on ecosystem services mapping methods and utilized publications within their reference lists to inform our analysis. Table 1 also therefore lists the number of articles each cites, which created our entire review dataset of 1,045 publications (including repetition between reference lists).

Table 1. Summary of reviews emerging from the first round of the methodological review.

Review		Number of papers cited within review
[26]	de Araujo Barbosa, Caio C., Peter M. Atkinson, and John A. Dearing. "Remote sensing of ecosystem services: a systematic review." *Ecological Indicators* 52 (2015): 430-443.	199
[27]	Andrew, Margaret E., et al. "Spatial data, analysis approaches, and information needs for spatial ecosystem service assessments: a review." *GIScience & Remote Sensing*52.3 (2015): 344-373.	144
[28]	Crossman, Neville D., et al. "A blueprint for mapping and modelling ecosystem services." *Ecosystem services* 4 (2013): 4-14.	113
[19]	Englund, Oskar, Göran Berndes, and Christel Cederberg. "How to analyse ecosystem services in landscapes—A systematic review." *Ecological indicators* 73 (2017): 492-504.	100
[29]	Harrison, Paula A., et al. "Selecting methods for ecosystem service assessment: A decision tree approach." *Ecosystem Services* (2017).	109
[30]	Maes, Joachim, et al. "Mapping ecosystem services for policy support and decision making in the European Union." *Ecosystem Services* 1.1 (2012): 31-39.	91
[5]	Malinga, Rebecka, et al. "Mapping ecosystem services across scales and continents–a review." *Ecosystem Services* 13 (2015): 57-63.	54
[24]	Martínez-Harms, María José, and Patricia Balvanera. "Methods for mapping ecosystem service supply: a review." *International Journal of Biodiversity Science, Ecosystem Services & Management* 8.1-2 (2012): 17-25.	42
[31]	Schägner, Jan Philipp, et al. "Mapping ecosystem services' values: Current practice and future prospects." *Ecosystem Services* 4 (2013): 33-46.	112
[32]	Wolff, S., C. J. E. Schulp, and P. H. Verburg. "Mapping ecosystem services demand: a review of current research and future perspectives." *Ecological Indicators* 55 (2015): 159-171.	81

Interestingly, even with our focus on agriculture within the search terms, only two of the ten use agriculture as a central focus when discussing ESS, the remainder mention it superficially. We decided to continue to utilize the same review papers given that methods are not specific to any particular type of landscape. We then analyzed the papers for key methodological concepts and the scale of their application. This creates our novelty and differentiates us from other reviews, for example, Malinga et al. [5] who also have a focus on scale but instead summarize the number of mapping studies at different scales, whereas we are focused on the methods used at each scale.

The text of each review paper was analyzed to identify methods that could be applied in mapping of ecosystem services, with a particular focus on those relevant for mapping ecosystem services listed in Figure 1. For further detail, we used citations from these review papers to collect further information. Section 3 presents the main types of mapping methods found in this subset of the literature, and informs section 4 which discusses the relationship with scale.

3. Literature Review - Different methods of ecosystem services mapping

Our focus in reviewing the literature was to identify what methods exist that create spatially disaggregated data regarding ecosystem services (particularly in agricultural ecosystems). We identified eight main methods, outlined below.

3.1. Remote sensing

Satellite remote sensing or Earth Observation (EO) has been widely used for mapping a variety of ESS, and nine out of ten review papers discussed it [5,19,24,26–31], including both services provided by agricultural ecosystems and services that support agriculture. Satellite data provides continuous spatial coverage over large areas, and consistent and repeatable measurements. It allows scaling up from field observations to the landscape level, and many EO products are globally available. However, unless validated against 'ground-truth' data, which is not always possible, EO-derived information can sometimes be based on false interpretations and can give a false sense of accuracy [33].

Most EO-based studies have focused on assessing 'potential' ESS rather than 'realized' ESS (i.e. the supply of services rather than the demand for those services or the human-wellbeing benefits) [34]. While EO data can provide important information for assessing ESS demand – i.e. the distribution of settlements and built infrastructure in the landscape – so far this approach has not been widely applied [32]. Assessing ESS demand and benefits requires careful integration of EO data with social-ecological and cultural information.

There are two main approaches for remote sensing of ESS: (i) land use land cover (LULC) classification and (ii) continuous surface biophysical variables (e.g. Leaf Area Index). For LULC based approaches, typically a set of land cover or habitat types are identified, and the capacity of each of these land cover types to provide various ESS is assessed. This information is combined with a classified map of the region and weightings are applied to the land cover classes to generate a map of potential ESS availability at the landscape scale. Often discrete land cover classes are used; however, fuzzy classification methods can be used to capture environment gradients by giving the proportion of each class within each pixel rather than identifying a single land cover type. An alternative approach is to use continuous surface biophysical variables. For example, vegetation indices derived from optical satellite imagery can be used to monitor provisioning services such as crop yields and forage availability [26,35].

There are several existing global, regional and national scale land cover maps (e.g. see Table 2). These products vary in their characteristics, and hence their relative advantages and limitations. The applicability of these maps for any particular ESS assessment depends on the scale of the analysis and the location of the study area. The accuracy of the land cover map is critical for ensuring the accuracy of the ESS assessment and hence rigorous accuracy assessment is ideally required [36]. Some studies produce their own land cover maps to overcome limitations of existing maps and to generate maps which are relevant to the local context. The accuracy of land cover maps can be optimized by using state-of-the art classification algorithms such as support vector machines, neural networks and random forest classifiers, which offer improved accuracies compared with traditional maximum likelihood classifiers, and by including textural information, ancillary data (e.g. elevation), multi-angle and multi-temporal imagery as input datasets [37]. The production of land cover maps is considerably easier than it once was, with more and more satellite datasets become freely available and cloud-based platforms such as Google Earth Engine allowing rapid processing of multiple images. Furthermore, data is now often provided in analysis ready format with many pro-processing steps already applied, such as the Landsat surface reflectance products. A key advantage of EO data for ESS assessment is the ability to assess changes over time. However, few studies have fully exploited the potential of EO data for investigating long term trends in ESS availability, as this has been identified as a future priority for advancing monitoring of ESS with EO [34].

3.2. Biophysical and ecological modelling

Biophysical and ecological models capture different processes and functions that control the availability of ESS and is another popular method, with nine of our review papers discussing it [19,24,26–32] The most commonly used biophysical and ecological models that can be relevant in agriculture are: soil erosion models like the Universal Soil Loss Equation (USLE) model [38], species distribution models [39], linear programming models [40], and state and transition models [29]. All contribute to an understanding of the ecological and biophysical functions for provisioning and regulating ESS.

At the fundamental level, studies can spatially map information from these models related to production harvests or volumes for provisioning ESS, where the information can be relatively easy to acquire. However, the type of data available is dependent upon the exclusive property rights. For instance, harvest volumes for timber resources are likely to be more difficult to obtain in areas with poorly defined property and tenure rights [28]. For such instances, more complex models have to be applied that links household demographic with natural resources. Also within provisioning ESS modelling, detailed commodity mapping can be completed by linking agricultural simulation process models to land use, soil and climate variables [29]. Similarly, subsistence food production can also be modelled and mapped, for example wild food sources from hunting data [41]. There are also models available for mapping basin-scale water balance functions that link evapotranspiration, precipitation and water holding capacity. Few of these models are suitable when detailed biophysical and land cover data are not available, although some work robustly with limited spatial data.

Mapping of regulating services is difficult and mostly relies on proxies. Modelling of air quality regulation and climate regulations, for example is studied in terms of leaf area index, and pollutant concentrations [28]. However, mapping then becomes relatively difficult as they are not expressed in terms of air quality variables, but are embedded in factors determining variations. Other services like moderation extreme events are modelled and mapped based on the availability of different vegetation and soil type to retain water that enhances infiltration and delays the time to reach flood peak [28]. As such, more sophisticated models are required which tend to be time consuming, expensive and requires technical expertise, for example hydrological models that depend upon topographical and geological data, vegetation cover, and management practices.

Even with the representation of modelling within ESS mapping, there are certain ecosystem services that are crucial to human wellbeing that have not been well documented and thus not mapped yet, usually due to relatively smaller scales of process. Pollination and biological control are such examples, where proxy LULC data, crop yields, climate and weather conditions, and required habitats can be used to study them [28]. Nevertheless, fewer attempts have been put to map these services [42]. Within our review paper dataset, there is not consensus regarding the choice of which model to use in mapping categories of ecosystem services. And indeed, there is wide recognition within the review papers that modelling-based studies can be limited in their accuracy given the often larger spatial scale of their focus and heterogeneity within landscapes in reality.

3.3. Agent based modelling and integrated assessment modelling

Agent based modelling (ABM) has recently received attention as a potential bridge between larger-scale quantitative biophysical modelling and more localized social, often qualitative, data, creating integrated social-ecological system models and is mentioned in three of the review papers [26,29,30]. ABM offers ways to replace differential equations, probabilities of populations, and decision rules with the provision of appropriate environmental feedbacks, by modelling the actions of humans on the environment [43]. However, there are few examples of ABMs that have used to explicitly model and map ecosystem services as a result of human behavior and ecological processes in agricultural landscapes. However, conceptual models exist [44], as do studies combining both ABM and biophysical modelling without mapping [45], and those including mapping but studying non-agricultural ecosystems, for example a study in Nepal to understand the soil nutrient dynamics which used ABM to establish a relationship between community decisions making and biophysical processes [43]. Moving the field forwards could include integrating other ecosystem service models that include feedbacks between social and ecological components, alike agent based models [29].

SImulation of Terrestrial Environment (SITE) is one of such modelling package developed to understand land use dynamics. Similarly, other models like Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) and Integrated Assessment Platform (IAP) can spatially analyze the impacts of different social and demographic attributes to provide multiple scenarios on ecosystem services [46]. Given the increasing popularity of ABM and integrated models, it is assumed to be a useful method in mapping ESS, but appears to be currently underutilized.

3.4. Non-market economic valuation of ESS

ESS are defined by the way in which people attach value (monetary or non-monetary) to them. Historically, studies that have attempted to estimate ESS values in monetary terms using mapping exercises [4,31,47,48] are more common than those assigning non-monetary values (see section 3.6), and are referred to in the majority of reviews [19,27–32]. Placing a non-market economic value on ESS can clearly induce agricultural policy makers to design desirable strategies in ecosystem management. However, though provisioning services have markets and incentives to produce and conserve them, many other ESS lack markets which makes them difficult to value. In addition, people value agricultural ESS differently, which makes it difficult to obtain a single ESS value that represents multiple interests of producers, consumers, and other stakeholders. As such, the value of ESS can be estimated either by determining the willingness to accept (WTA) or willingness to pay (WTP) from hypothetical questions and scenarios [49].

There are number of methods for economic valuation of agricultural ESS: market prices, public pricing, travel cost methods, contingent valuation and stated preference methods, replacement cost methods, restoration costs, production functions, hedonic pricing methods, factor income methods, and choice modelling methods [46,49]. Regardless of the methods used, value of agricultural ESS varies across spatial context and can therefore be represented on maps by estimating spatial difference between ESS supply and demand [4,31,47,48]. The spatial map can include agroecosystem parcels, ecosystem units, and beneficiaries. A review of agricultural ESS studies showed that most of the assessment is carried out through economic measures, conducted at one site and then transferred to others [50], which was heavily critiqued for neglecting spatial differences as ESS considerably vary in scale and scope [51]. There are fewer non-monetary assessments, yet approaches to quantify those agricultural ecosystem services are equally important and are outlined below.

3.5. Expert opinion and professional judgement

As alluded to above, quantifying and mapping ESS is complex. Although translating quantifications of ESS to maps has been widely utilized and welcomed as a communication tool of ecosystem service availability [52], it can sometimes mask the complications of equity dynamics that are integral to human societies and influence who has access to which ESS. Expert opinion and professional judgements can provide a wide array of information where it was lacking, and in doing so, can increase the effectiveness of research, creating what appears to be a simple ESS map but which is a result of complex quantitative algorithms, proxies, qualitative judgements, expert estimates, and communicative visual goals [46]. A GIS technician or a modeler, for example, cannot produce maps without the professional knowledge from an ecologist, economist, or social scientist, who can validate, elucidate, improve, and legitimize maps to be applicable for an explicit context. In this context, the review papers referencing expert opinion are referring to science-based expertise [24,28–32], not traditional knowledge (see section 3.6 for further discussion of this).

For example, a study conducted in Spain used expert interviews (environmental managers of the protected area, environmental experts from the National Park Agency and the regional environmental agency, and scientists working in the study areas belonging to universities and research institutions) to explore spatial analyses of ESS demand and supply flow in a national park [53]. The objective of this study was to examine and map the ESS provided by the national parks. Perceptions of experts were mapped on the relative capacity of the protected areas to provide services and also the differences in ESS flow among protected and unprotected national park territories. The study was able to identify degraded areas and the drivers related to existing threats to ESS. Another study used professional judgement approach to identify how vegetation management manipulates ESS at a landscape scale and showed that restoration or removal of soil vegetation gives certain mosaics of vegetation classes that produce different ESS [54]. In both cases, expert judgement was utilized to 1) validate spatial data, 2) provide social context, and 3) inform management decisions.

3.6. User perceptions and community values

As identified multiple times above, ESS appraisal needs an integrated evaluation that considers socio-economic dimensions, in particular values, along with ESS supply and demand. Nevertheless, many publications use the word "value" in ESS assessments to indicate financial value [55] whilst neglecting societal, cultural, spiritual, and aesthetic importance. To overcome this gap, recent literature is focused on cultural valuation [17,56–58], referred to in multiple review papers [28–30,32]. The increase in publication on cultural ESS coincides with the establishment of the Intergovernmental Platform of Biodiversity and Ecosystem Services (IPBES) [59]. One of the challenges highlighted by IPBES in relation to cultural ESS valuation is the inclusion of user's knowledge systems and community pluralism. Formalizing socio-cultural values in a methodological framework that includes needs and aspiration of ecosystem dependent population is crucial. User perceptions and community values can be understood as an umbrella term that analyzes and maps ESS in terms of non-monetary units, under which there are other terms like social valuation, qualitative valuation, subjective assessment, and deliberative valuation that uncovers the individual and collective perceptions of ESS without economic matrix.

One of the common strategies under this broader method is preference assessment. Under this method, there can be many exercises like ranking, rating, selection mechanisms, and preference weightage. For example, preference assessment strategies have been employed with farmers to monitor their preference and perceptions towards ESS [56], in order to examine the relationship between threats to agricultural ESS and users' perceptions and community values of those ESS and create appropriate management plans. Similar studies utilize a multi-method approach to support ESS mapping and community values developed, for example community's perceptions of ESS use, values, and changes were identified through key informant interview, focus group discussions and household interviews in Koshi River basin in Nepal [60]. The results from this study, when matched and cross validated with other literature and advance remote sensing data, found that this method was more vigorous and provided more articulation on ESS values. The success of this paper can also be linked with different narratives on values of ESS available through focus group discussions, which focused on the incorporation of local knowledge systems.

3.7. Participatory mapping

Participatory mapping covers a range of techniques that assess the distribution of ESS as per the preference or perception of users, managers, or stakeholders, either by surveys, workshops, or focus group discussions [46]. Methods range from low-resource and low-cost to high-resource and high-cost, with the chosen approach dependent on how the final product will be utilized, the expected impact of the tools to be utilized, the expected accuracy of the final product, and the resources available [61,62]. Different ranges of technological support have been utilized in its implementation, including none and participants drawing their own maps, to satellite images, aerial photographs, and geographic information systems (then referred to as participatory geographic information systems (PGIS)) [62,63]. The overall technique enables different stakeholders (and often a range of stakeholders) to participate by spatially representing their values and knowledge in ESS [18,64] and is particularly applied to ESS mapping that requires location-specific traditional ecological knowledge, as discussed in five of the review papers [24,28–30,32].

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Often considered as most pragmatic and practical, participatory mapping tends to be used to generate knowledge in areas where there is lack of data available for particular ESS. The validity of participatory mapping is sometimes contested, with some arguing for lower accuracy and reproducibility, but recent studies have shown that LEK is not significantly different to expert knowledge, and the use of participatory mapping is evident through the application of its results in land-use planning, conservation management and natural resources management [63,65]. Additionally, studies demonstrate geographical differences among individually and collectively held values across the landscapes, commonly not elucidated by other mapping methods - for example, variations in ESS valuation among and between different local community and experts, men and women, and among different socio-economic classes [18,66]. Therefore, participatory mapping must be done in a manner aware of power dynamics within the community in order to be representative, but allows the capture of a diverse range of values whilst giving the community a space for participation in spatial planning.

3.8. Photo-elicitation

Another layer of spatial data regarding values of agricultural ESS can be created using photo-elicitation methods, by translating user's visual knowledge and preferences into ESS values. A relatively new addition to ESS mapping methodologies, only two of the reviews discuss it [29,30]. Geo-referenced repeated photography, as a part of photo elicitation technique, can be used to monitor long-term ecological changes by comparing recent photographs with baseline photographs both at aerial and terrestrial level. Comparison of current photographs with historical photographs demonstrates change or persistence of cultural landscape structures [67]. Terrestrial photography is mostly used in qualitative research at a focused location, while additional aerial photographs provides wider and quantitative coverages of the data [68,69]. Repeated photography as a diachronic photo-diary allows the depiction of the community's perspective in assessing environmental services and the images can be used as a prompt to reach consensus among local community members [69]. Repeated photographs can also make groundtruthing more convincing for the general audience. However, given that it requires historic photographic records, this technique cannot be used in remote areas which are seldom expedited and is often difficult to expand to a broader scale. Nevertheless, this technique can be useful tool to gain insight into localized change in ESS mapping, which allows researchers to identify key trajectories for broader research, and to corroborate results from other mapping exercises.

Additionally, one-off photo-elicitation studies can be used to allow the researcher and the research subject(s) to mutually interrogate photographs on a given theme [70], for example ESS values. Participants can be asked to take geo-referenced photographs of features they class as 'significant' [71], which can then be used in an interview as prompts to explore values and motivations. Whether repeat or one-off, photo-elicitation is based on personal construct theory, which suggests that the values that emerge through the completion of constrained tasks such as photo-elicitation can sometimes be more true to deeply held personal beliefs than direct questioning in surveys or interviews [72,73]. However, we presume given the time and resource requirements, it is less commonly mentioned in the literature.

4. Discussion

There is a need to identify where stockpiles and flows of ESS are located, and who has access to them, within ecosystems - particularly agricultural ecosystems - so that they can be monitored and sustained. In addition, understanding the condition of and threats to these ESS facilitates management that allocates resources to areas in need. Mapping is emerging as a consistent tool used to address such challenges with the overall goal of managing ecosystem services sustainably [29,30]. Section 3 demonstrates that this is still a burgeoning field, and so there are few studies that study the whole management process, partly because of lack of policy directives but perhaps also because of lack of pertinent data and tools [30].

4.1. Distribution of methods by scale

Studies mapping agricultural ESS use different spatial scales, from local to global. One review in our dataset focused on remote sensing data found that 53% of the total systematically reviewed articles are focused at municipality scale, followed by 21% at the province scale and 19% at the national scale [5]. However, selecting a particular mapping method is often difficult as the variety of factors are considered when studies select a mapping method. The scale and purpose of the study, relative ESS at stake, type of research, available financial resources and policy priorities often dictate the mapping methods used [29]. Figure 2 summarizes the different spatial scales and the methods which are applied at each of these scales, based on our review of the literature.

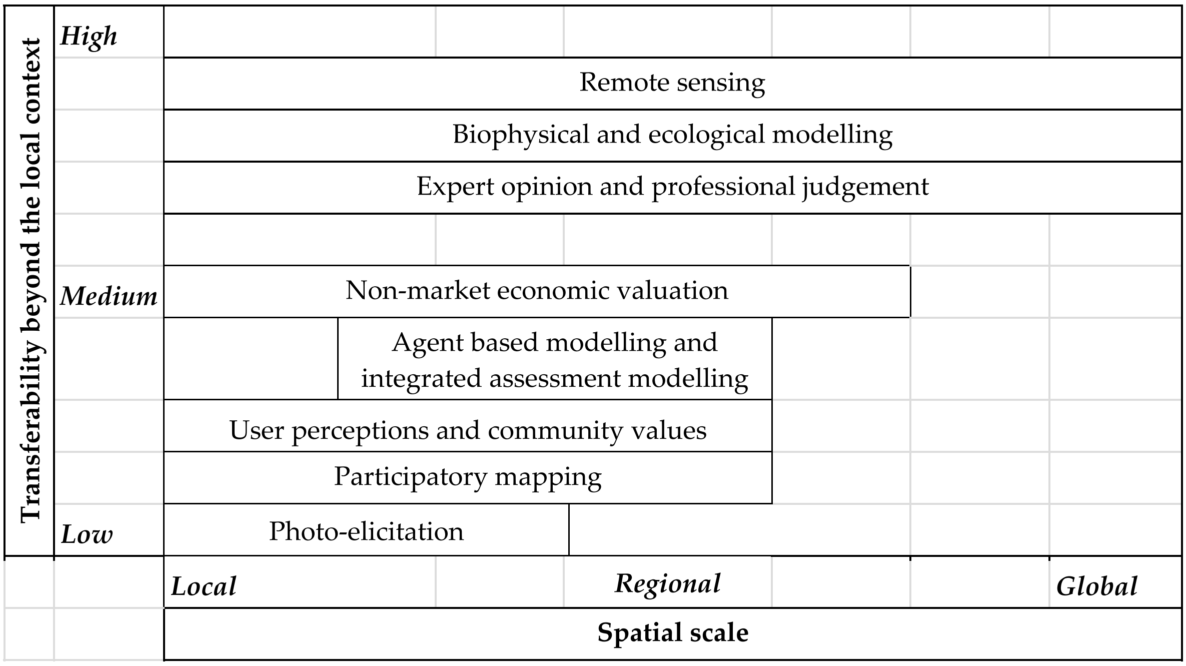

Figure 2. Ecosystem service mapping methods arranged by scale and transferability beyond the local context. Some methods cross-cut multiple spatial scales, i.e. remote sensing can be used from the local (down to 30m resolution) to the global.

Scale is an important theme of this study as it determines the possible configuration of ESS, the supply of ESS spatially in response to socio-economic and biophysical drivers, and the type of mapping methods to be used. Our literature review revealed some clear trends. It is notable that key mapping methods that are used today can mostly be applied at the regional scale, but that methods are then differentiated by relevance to the local or global scale.

Crossing the regional and global levels, remote sensing, biophysical and ecological modelling, expert opinion and professional judgement, are mostly used. Indeed, there are several initiatives focused on developing global indicators of ESS from remote sensing data (e.g. IPBES). Whilst economic valuation can be used for global level studies [4], it is more commonly applied at smaller spatial scales given issues in consistent valuation at larger spatial scales, and similarly there is the potential to use agent based and integrated modelling across a range of scales, but the global scale is difficult due to the lack of global decision making. Finally, user perceptions and community values and participatory mapping are most commonly used at the local (i.e. community) scale but can be scaled up, whereas photo-elicitation is commonly used at the local level only.

4.2. Cross-scale interactions

In the future, attempts should be made to develop more systematic cross-scale methods that not only covers the broader array of ESS but also aids in evidence-based policy development and ecosystem management, as echoed in other review papers [5,24,28]. As mentioned in section 3, many ESS studies are based on secondary or proxy data – particularly at larger spatial scales given associated costs of primary data collection. There is little conversation regarding accuracy and errors associated with relative transferability of these methods; on the contrary, the body of literature on economic valuation of ESS relies on transferability [74,75]. For any mapping method to perform well, it becomes crucial to identify the contextual information that predicts the relative performance potential of each method and to understand how reliability is visualized across those context – generally most easily done at the local scale. However, social-ecological systems are hierarchical in themselves with many overlapping feedback loops, and thus the context changes across space and time. In this regard, selecting an ESS mapping method with a focus on a single scale may obscure crucial processes that only become obvious at other scales. Therefore, mapping studies should incorporate multiple methods to collect data across multiple scales.

4.3. Cross-scale methodologies

Multiple methods are preferable due to trade-offs between transferability and relevance of individual methods across scales. Mapping methods focused at local scale are considered more rigorous than approaches designed at regional and global scale [63], but this also highlights a mismatch in the literature, as many studies on ESS studies are broad-scale assessment with few primary-data based measures that are then extrapolated to entire regions. Even though these assessment and mapping modalities may be crucial for creating global awareness on conservation and valuation of available agricultural ESS, broader studies reduce the heterogeneity of ESS (for example in biophysical quality, spatial configuration, and social values). On the other hand, local scale assessments are focused at a small spatial area and though this may help in identifying plausible scenarios and mapping changing prospects of ESS, these mapping exercises may lack scope and scale that are relevant for policy interventions and trade-offs between decision making over multiple ESS and multiple scales. To avoid both of these situations, a research design that integrates multiple scales is required.

Therefore, we present Table 2 as a framework for selecting relevant methods for an agricultural ESS mapping study, in that once you have identified your scales of interest (ideally a focal scale and one scale above and below, as per social-ecological systems theory [76]) the table demonstrates which tools are relevant. Given agricultural ESS are context dependent, each method will not be applicable everywhere – the choice will depend on data and knowledge availability in the scales of interest and relevance for management or policy. Integrated studies like this are becoming more popular, and provide more successful harmonization of strengths whilst reducing weaknesses of the individual mapping methods. For example, combining remote sensing data and participatory mapping [63]; field-level models based on primary data with remote sensing [35]; and repeat photograph with participatory mapping [18].

4.4. Omo-Turkana Research Network - SIDERA

The integration of multiple methods may be most practical in data-poor regions where primary data is unavailable, and a selection of in-situ data generation methods such as participatory mapping, expert opinion, user perception, and agent based modelling must therefore be combined with global and regional data co-generation methods like biophysical modelling and remote sensing. The authors are all affiliates of the Omo-Turkana Research Network, collaborating on the project "Shifting In/Equality Dynamics in Ethiopia: from Research to Application" (SIDERA) in the transboundary Omo-Turkana river basin in SW Ethiopia and N Kenya. The Omo-Turkana basin lacks locally-relevant maps of agricultural ecosystem services, and the primary data and expertise to inform such

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maps, but is rich in traditional ecological knowledge. Agricultural ESS in this basin are particularly important to document given the rapid ongoing change in land use in the area. Therefore, utilizing the framework, we have created a cross-scale research design that allows us to compare availability, access, and values of crop-based and animal-based agricultural ESS, change in these, and the resulting impacts on livelihoods and conflict in the basin. We are combining multiple methods, at multiple scales, from local to national, as demonstrated in Figure 3.

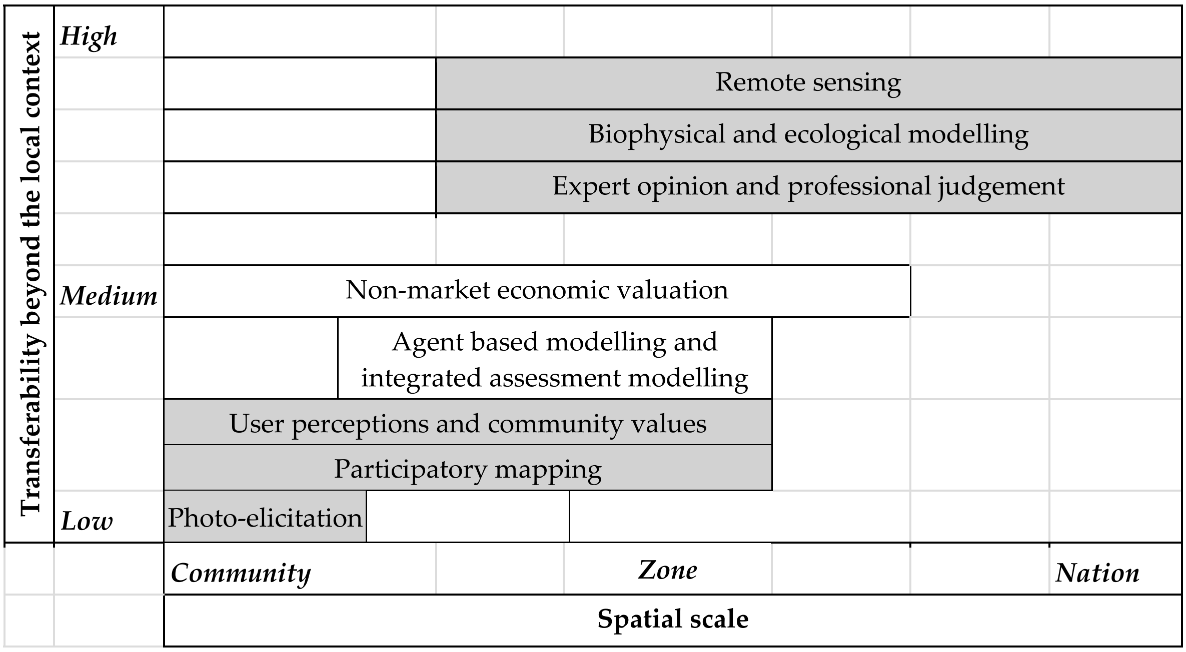

Figure 3. Ecosystem service mapping methods being utilized in the SIDERA project. We have adjusted the spatial scale to our context, and methods shaded in grey are utilized and expanded on below.

- Photo-elicitation. Not repeat photography, but one-off images and videos of elements of the landscape community member's values.
- Participatory mapping of ecosystem services at the community, local government unit, and river basin scales. Carried out with groups representing local communities with different livelihood strategies, local and national government, and national and international non-governmental organizations.
- User perceptions and community values of those ecosystem services. Carried out with groups representing local communities with different livelihood strategies, local and national government, and national and international non-governmental organizations.
- Expert opinion and professional judgement from local elders, national and international scholars, providing primary data via transect walks, secondary data, and context to knowledge gaps in the mapping.
- Biophysical and ecological modelling, scaling up local ESS availability and value to create basin-wide maps.
- Remote sensing, at 30 m resolution (using Sentinel-2 and Landsat data in Google Earth Engine) to produce classified LULC maps.

Our intention is to test this research design for accuracy and efficiency of resources with one group within the river basin, then scale up data collection to the remaining groups in order to create local scale land cover maps with ecosystem service availability, access, values, and change layers.

5. Conclusions

When mapping agricultural ecosystem services, global approaches tend to rely on expert knowledge, models and EO-derived land cover classes and biophysical variables. Local approaches often involve substantial fieldwork to collect social-ecological data in a participatory manner regarding user perceptions of values. As highlighted above, local data collection allows researchers to overcome the limitations of existing maps and generate bespoke land cover maps which are better tuned to the local context. Thus a focus on producing a set of global ESS products has its limitations - while it will certainly lead to advancements in our understanding of ESS availability at the global scale, such products are unlikely to provide sufficient information for decision-making at local or national scales [77]. Hence, an adaptive approach is required depending on the context that integrates mapping methods appropriate for multiple spatial scales. Our framework summarizes the current state of knowledge on these methods and their spatial suitability. Future efforts should be made to develop user friendly software tools and provide training to support the generation of locally relevant land cover maps and other remote sensing products that are tailored to local context. But this will not negate the fact that investigation of agricultural ESS should be carried out a range of scales to support management and policy decisions at all scales.

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