Interoperable Workflows for Ecosystem Service Assessments: Applications in Science, Policy, and Education

Lacayo-Emery, Martin Ariel

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Professeur Anthony Lehmann

Interoperable Workflows for Ecosystem Service Assessments: Applications in Science, Policy, and Education

THÈSE

Présentée à la Faculté des sciences de l'Université de Genève
Pour obtenir le grade de Docteur ès sciences, mention Sciences de l'Environnement

Par

Martin Ariel LACAYO-EMERY

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Thèse de Monsieur Martin Ariel LACAYO-EMERY

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«Interoperable Workflows for Ecosystem Service Assessments: Applications in Science, Policy, and Education»

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N.B. - La thèse doit porter la déclaration précédente et remplir les conditions énumérées dans les "Informations relatives aux thèses de doctorat à l'Université de Genève".

For both my families, given and chosen, without whom nothing would be possible.

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ABSTRACT

Ecosystem service assessments evaluate the benefits humans derive from nature and are used to determine tradeoffs under different scenarios to help achieve desired outcomes. This is especially important with increases in resource consumption under the uncertainty of climate change. One area of particular concern is water related ecosystem services because of their critical importance to all life. The complexity of ecosystem service assessments mirrors that of the natural systems they evaluate, and as in other areas of science there is increasing recognition that reproducibility is a challenge. Often this results from lack of sharing or incomplete reporting on the data and analysis methods, frequently driven by publication constraints. Regardless, reproducibility in science is critical, because it increases certainty in results and accelerates new knowledge as a foundation for other studies. An intentional and active approach to reproducibility is therefore important, and in many cases a solution is found through an emphasis on interoperable workflows.

Geographic Information Systems (GIS) have a long history of interoperable data protocols; and spatially explicit ecosystem service assessments can benefit from the same approach. The Open Geospatial Consortium Web Services (OWS) are a collection of standards for the exchange of geographic data and geoprocessing parameters across networks including the Internet.

The Soil and Water Assessment Tool project for Switzerland in the 21st century (SWATCH21) links eco-hydrologic processes and services to aquatic biodiversity at river and catchment levels and benefits from the interoperable exchange of data in particular because of its need for diverse data sources and methods. These benefits have value beyond SWATCH21 and were generalized into a fully OWS compliant workflow framework tool called the Ecosystem Service Web Service (ESWS).

The ESWS takes a new approach to quantifying the benefits that humans derive from nature. It proposes to alleviate some of the technical challenges of reproducibility through improved interoperability with the use of open web standards for ecosystem

service assessment, facilitating creation, iteration, and dissemination in a seamless way. It can increase accessibility while allowing method and data providers granular access control. Lastly, the fault tolerant nature of these workflows allows models to be set up with future datasets and executed once the datasets are available, thereby freeing human resources.

This interoperable approach streamlines collaboration, automation, and curation, while providing an open interface through which novel advances can be incorporated. It achieves a new level of interoperability because each transition between processing steps employs standards that ensure cohesive workflows across models and platforms. This imparts a modularity that can be examined and extended at every step for maximum flexibility. Through the ESWS, veterans of ecosystem service assessments can further standardize and share their methods while juniors can more easily achieve high quality results.

ESWS has implications for ecosystem service assessment science, policy, and education. ESWS workflows can improve efficiency and reproducibility in science. In the policy arena, ESWS can improve communication and collaboration at the science-policy implementation interface. Finally, in the area of education, where there has been increasing emphasis on online learning, ESWS can facilitate learning through serious games, web based analytical workflows, and equitable access to ecosystem service assessment software.

RÉSUMÉ

L'évaluation des services écosystémiques permet d'évaluer les avantages que l'homme retire de la nature et sert à déterminer les compromis à faire selon différents scénarios pour atteindre les résultats souhaités. Ceci est particulièrement important avec l'augmentation de la consommation des ressources dans le contexte de l'incertitude du changement climatique. Les services écosystémiques liés à l'eau constituent un domaine particulièrement préoccupant en raison de leur importance cruciale pour toute forme de vie. La complexité des évaluations des services écosystémiques reflète celle des systèmes naturels qu'elles évaluent et, comme dans d'autres domaines scientifiques, il est de plus en plus reconnu que la reproductibilité est un défi. Cela résulte souvent d'un manque de partage ou d'un rapport incomplet sur les données et les méthodes d'analyse, souvent motivé par des contraintes de publication. Quoi qu'il en soit, la reproductibilité en science est essentielle, car elle accroît la certitude des résultats et accélère l'acquisition de nouvelles connaissances qui servent de base à d'autres études. Une approche intentionnelle et active de la reproductibilité est donc importante, et dans de nombreux cas, une solution est trouvée en mettant l'accent sur les flux de travail interopérables.

Les systèmes d'information géographique (SIG) ont une longue histoire de protocoles de données interopérables ; et les évaluations spatialement explicites des services écosystémiques peuvent bénéficier de la même approche. Les services Web de l'Open Geospatial Consortium (OWS) sont une collection de normes pour l'échange de données géographiques et de paramètres de géotraitement à travers des réseaux, y compris l'Internet.

Le projet d'outil d'évaluation des sols et des eaux pour la Suisse au XXIe siècle (SWATCH21) relie les processus et les services éco-hydrologiques à la biodiversité aquatique au niveau des rivières et des bassins versants et bénéficie de l'échange interopérable de données, en particulier parce qu'il nécessite diverses sources de données et méthodes. Ces avantages ont une valeur au-delà de SWATCH21 et ont été généralisés dans un outil cadre de flux de travail entièrement conforme aux OWS, appelé Ecosystem Service Web Service (ESWS).

L'ESWS adopte une nouvelle approche pour quantifier les avantages que les humains tirent de la nature. Il propose d'atténuer certains des défis techniques liés à la reproductibilité en améliorant l'interopérabilité grâce à l'utilisation de normes Web ouvertes pour l'évaluation des services écosystémiques, facilitant ainsi la création, l'itération et la diffusion de manière transparente. Elle peut accroître l'accessibilité tout en permettant aux fournisseurs de méthodes et de données un contrôle d'accès granulaire. Enfin, la nature tolérante aux pannes de ces flux de travail permet de configurer des modèles avec de futurs ensembles de données et de les exécuter une fois que les ensembles de données sont disponibles, libérant ainsi des ressources humaines.

Cette approche interopérable rationalise la collaboration, l'automatisation et la conservation, tout en offrant une interface ouverte permettant d'intégrer de nouvelles avancées. Elle atteint un nouveau niveau d'interopérabilité car chaque transition entre les étapes de traitement utilise des normes qui garantissent des flux de travail cohérents entre les modèles et les plateformes. Cela confère une modularité qui peut être examinée et étendue à chaque étape pour une flexibilité maximale. Grâce à l'ESWS, les vétérans de l'évaluation des services écosystémiques peuvent normaliser et partager davantage leurs méthodes, tandis que les débutants peuvent plus facilement obtenir des résultats de haute qualité.

L'ESWS a des implications pour la science, la politique et l'éducation en matière d'évaluation des services écosystémiques. Les flux de travail ESWS peuvent améliorer l'efficacité et la reproductibilité de la science. Dans le domaine des politiques, l'ESWS peut améliorer la communication et la collaboration à l'interface entre la science et la mise en œuvre des politiques. Enfin, dans le domaine de l'éducation, où l'accent est mis de plus en plus sur l'apprentissage en ligne, les ESWS peuvent faciliter l'apprentissage grâce à des jeux sérieux, des flux de travail analytiques basés sur le Web et un accès équitable aux logiciels d'évaluation des services écosystémiques.

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1. INTRODUCTION AND THEORETICAL FRAMEWORK

1.1 Background

Navigation, from the Latin *navis agere*, once meant to lead a ship, but in the more than 7,000 years since humanity began sailing, we have moved from navigating the seas to navigating the vastness of space. Now one can even explore virtual reality and information spaces. Our global society has yielded incredible technologies that have allowed us to prosper and multiply, but nonetheless we are adrift, heading towards a place where our ecosystem will collapse. The Sustainable Development Goals are a map that will lead to a better future for all. The 17 goals, 169 targets, and 247 indicators represent a global consensus that charts a course to safeguard the environment while attaining socially just, sustainable development (United Nations, 2015). This map cannot simply be read, but rather requires extensive information and knowledge to understand.

Ecosystem services are the benefits humans derive from nature (Daily et al. 2009). Their assessment has been identified as essential information for achieving the Sustainable Development Goals (Costanza et al., 2016; Geijzendorffer et al., 2017; Kubiszewski et al., 2017). However, not all the data needed to conduct ecosystem service assessments is broadly available (United Nations, 2014). It can be diffuse and fragmented, in different formats, and not readily amenable to data harmonization. Improvements in data acquisition and processing are needed to aid in the production of ecosystem service assessments.

The completion of an ecosystem service assessment introduces dissemination issues. The common practice of sparse reporting on methods and limited sharing of data confound the ability to dissect an assessment and reproduce the results (Baker, 2016; Nüst et al., 2018). Much as the challenges to the production of an assessment are focused on access, so too can be their reproduction. Therefore, this can be framed as an interoperability issue. If producers and consumers of assessments had access to a streamlined way to bring data together, embed it in a workflow, and easily share the results, then they could contribute greatly to the science and practice of ecosystem service assessments.

This thesis proposes solutions to some of the technical challenges of ecosystem service assessments (Ramirez-Reyes et al., 2019) through the creation of a tool for interoperable workflows using web services for data acquisition, analysis, and replication. The intent is that an active and deliberate approach to interoperability can also diminish some of the challenges to science, the science-policy implementation interface, and education. My work here is interdisciplinary, drawing from the fields of environmental science, geographic information science, computer science, and computer systems engineering. I apply insights from these disciplines, as well as two decades of experience in geographic information science, to develop a web service solution to enhance spatially explicit ecosystem service assessments.

1.2 Research Problem and Questions

Ecosystem service assessments face several technical challenges, which limit the approach's capacity to provide timely, actionable knowledge about pressing environmental problems. In particular, there are challenges associated with using the wealth of existing datasets. In this thesis, I examine the problem these technical challenges present for the efficient, reliable execution of ecosystem service assessments using existing data. My concerns here extend from initial data acquisition through replication of results. I propose a novel solution and implement a proof of concept while contextualizing its advantages for science, the science-policy implementation interface, and education.

To this end, I ask the following research questions:

1.2.1 Why and how are ecosystem service assessments conducted?

Ecosystem service assessments operationalize the ecosystem service concept. Thus, designing and evaluating ecosystem service assessments requires an understanding of the ecosystem service concept itself. While there is no singular, universally agreed definition of ecosystem services (Fisher et al., 2009), broadly speaking they are understood as the benefits humans derive or receive from ecosystems (MEA, 2003). Section 2.1 provides a brief overview of the vast literature on the ecosystem service concept.

Next, assessing the source of technical challenges to ecosystem service assessment necessitates examination of the methods and tools commonly used to conduct them. Fundamental steps in conducting ecosystem service assessments include identifying the services to be assessed, selecting evaluation methods, applying those methods to analyze quantitative and qualitative data, and interpreting results (Dunford et al., 2018; Harrison et al., 2018). Ecosystem service assessment methods and tools are discussed in greater detail in Section 4.4.

1.2.2 What are the technical challenges for creating ecosystem service assessments using existing data?

Ecosystem service assessments model the current supply of services and how they change under different scenarios. The dynamics of services and their covariance can be determined through the evaluation of different scenarios This exploration of scenarios requires the support of a technical framework to gather data, iterate on models, and consolidate results that are increasingly used to inform environmental decision making. Technical challenges in any of those areas can derail ecosystem service assessments.

Use of existing data is clearly advantageous. Used singly and in combination, the plethora of existing data are potentially rich sources of information at spatial scales from the local to the global, and temporal scales from snapshots in time to observations of change over decades. However, using existing data also presents several distinctive technical challenges. First, data is often distributed and can require extensive time to manually gather and harmonize. Second, it can be challenging to use existing software to iterate on models while incorporating parameter calibration and fine-tuning algorithms to the real-world phenomena they represent, especially when often software is not designed in a manner that can be easily changed. Third, the consolidation and synthesis of results for diverse ecosystem services is complex because of their breadth. Further, this challenge is compounded by difficulties that arise from needing to integrate different data types in formats that are not readily combinable. These issues, which are the focus of this thesis, are especially evident in ecosystem service assessments that use existing data.

In Sections 2.1.1 to 2.1.3, I discuss ecosystem service assessments that use existing data at three different scales. Section 2.1.1 details water yield and flooding in a region of China. Section 2.1.2 explores coastal protection from storm surges and sea level rise in the United States. Section 2.1.3 discusses recreation and tourism throughout the global. In each section specific technical challenges are identified, and solutions are proposed.

1.2.3 What are the reproducibility challenges for ecosystem service assessments?

The "reproducibility crisis" is an emerging concern in GIScience (Nüst et al., 2018). As related spatially explicit analyses, ecosystem service assessments should be subject to similar concerns. When ecosystem service assessments cannot be reproduced, uncertainty about their validity as a basis for policy is inevitable. While historically, uncertainty analysis has been considered due diligence and a sufficient concession to contrary opinions, in a post-truth era, reproducibility is a critical defense against deniers.

Ecosystem service assessment also suffers from challenges to reproducibility. In the absence of shared data and methods the costs of reproducing a study often outweigh the rewards. Furthermore, in some cases it can become impractical or even impossible to gather the required data because increasingly rapid changes under climate change render ephemeral observations essentially irreproducible (Wolkovich et al., 2012). I discuss the challenges to reproducibility in science, in general, and geographic information science (GIScience), in particular, in Sections 1.3.4 and 1.3.5, respectively.

1.2.4 Is there an approach that can ameliorate the technical challenges for creation and reproduction of ecosystem service assessments?

The questions addressed in 1.2.1 to 1.2.3 are necessary precursors to answer this question of whether there is an approach that can ameliorate the technical challenges for creation and reproducibility of ecosystem service assessments. In addition, these sections survey the potential to resolve the research problem.

Over the course of approximately 10 years of work on ecosystem service assessments at many different scales and extents (Section 2.1), a series of challenges have become evident to me. Those challenges may be especially acute where ecosystem service assessments are conducted by teams of researchers who are spatially dispersed and/or whose members change over time. In such cases, the success of an assessment may well depend on the ability to share a complex workflow. With an intentional approach to interoperability, this process can be streamlined, benefitting both the assessment's originator, whether an individual or a team, as well as parties interested in reproducing it with interoperable data and methods for performing the analysis.

The ability to coordinate all these resources can be challenging for one's own work and even more so when collaborating or sharing with others. These challenges include data management topics, personal and organizational policies around access and sharing, and demands on computer resources. In the absence of interoperability standards, each of these require manual solutions that can be fragmented and irreconcilable. In contrast, use of standards facilitates the exchange of data and methods. Such exchange is a mechanism to distribute the source material required for an analysis and, thus, is essential for reproducibility. It is impossible to reproduce an assessment without access to the data or methods used to produce it. I discuss interoperability in Section 1.3.6. A webservice based approach to interoperability for production and reproduction of ecosystem service assessments is the original contribution of this thesis and, as such, is presented in depth in Chapter 3.

1.2.5 What implications does the technical solution pose for science-policy implementation interfaces?

The science-policy implementation interface is a coordinated, bi-directional relay of information between scientists and policy makers. Scientists provide the expertise to answer policy makers' questions and can guide the latter to areas where they may not have known questions could be answered. Policy makers provide scientists with the theme for exploration and areas where further information is desired. This requires trust in the methods of each and the ability to use those methods to generate information and communicate that information effectively. The methods and data that scientists and policy makers rely on must therefore be dependable and come from reliable sources. In addition to these sources using established standards of quality the resources must be provided with continuity and, except in rare occasions, not be subject to revocation. Continuity is important in the case of ecosystem service assessments because of the spatial and temporal scales and often ephemeral nature of phenomena that must be measured. In the absence of continuity, the ability for scientists to provide evidence-based reasoning is sabotaged. The very nature of reproduction and continuation studies require that data and tools not disappear. The science-policy interface breaks down when scientists no longer have the resources needed for their trade. I address the implications of the proposed technical solution for the science-policy implementation interface in Chapter 2.

1.2.6 What implications does the technical solution pose for education?

Technical solutions prove their value through application that is ultimately initiated by people. In order to apply technology people must have relevant knowledge and all the required resources. There have been massive shifts in recent years, especially in light of the pandemic, in how teaching is carried out and educational resources can be distributed. Learning through online platforms and MOOCs has become commonplace, in many ways echoing other technological shifts to the cloud. However, the materials required, such as data and software, are often supplied in an either simplified way, through file sharing, which does not build skills, or in an uncontrolled way through the heterogeneous delivery choices of third parties. The latter is an essential skill to be able to navigate, but this can frustrate new learners. In addition to implications for learners, the proposed technical solution has several implications for teachers. These are discussed in Chapter 5.

1.3 Theoretical Framework

This work is a novel and important improvement to the way in which ecosystem service assessment can be conducted. It is a multidisciplinary endeavor drawing on work in the fields of environmental science, geographic information science, computer science, and computer systems engineering. Each of these disciplines contributes to a solution for reproducible ecosystem service assessments. This chapter includes details on the *status* *quo* of ecosystem services, ecosystem service assessment methods and tools, workflows, reproducibility, reproducibility in GIScience, interoperability, and web services. Chapter 1 concludes with the structure of the thesis.

1.3.1 Ecosystem Services

Ecosystem functions such as the retention of water, soil, and nutrients give rise to ecosystem services including water supply, erosion control, and nutrient cycling that are critical for human well-being (Costanza et al. 1997; Daily et al. 2009; Ehrlich and Mooney 1983). This concept has been adopted widely as a means of explicitly linking changes in the environment and benefits to humans in spatial planning (R. S. de Groot et al., 2010), biodiversity conservation (Cardinale et al., 2012), and in the broader realm of sustainability science (Carpenter et al., 2009). The ecosystem services concept supports the contextualization and comparison of gains and losses that could result from action and inaction on various environmental policies and practices. Such analyses are increasingly important as climate change generates mounting uncertainty about the world's capacity to supply ecosystem services (Schröter et al., 2005)

The ecosystem service concept evolved out of the observation that the conservation movement, while successful in commanding attention in the international and national policy arenas, has largely failed to translate into meaningful action at the personal level (Daily et al., 2009). Consequently, meaningful progress toward conserving ecosystems and biodiversity continues to be elusive. Ecosystem service assessments, by quantifying services and making benefits explicit, are intended to motivate personal conservation values and actions (Armsworth et al., 2007).

There is momentous progress in both the science and software of ecosystem service assessment (Wood et al., 2018). The science has progressed in concert with international initiatives such as the Millennium Ecosystem Assessment (MEA, 2005), the Economics of Ecosystems and Biodiversity (TEEB, 2010), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Díaz et al., 2015). The evolution of theory in this field is also reflected in recent innovations such as greater precision in taxonomic systems used to describe and measure ecosystem services like the Common International Classification of Ecosystem Services (Haines-Young and Potschin 2018). The practice of conducting an ecosystem service assessment has also advanced with the development and extensive testing of specialized software (Kareiva et al., 2011; Sherrouse et al., 2011; Villa et al., 2014), as well as adopting software such as the Soil and Water Assessment Tool (Glavan et al., 2015; Liu et al., 2013; Vigerstol & Aukema, 2011) for new purposes.

The ecosystem service concept is an anthropocentric reframing of the environment to describe nature in terms of the benefits provided to humans (Costanza et al., 2017) Ecosystem services are commonly grouped into four categories: regulating, supporting, provisioning, and cultural (Figure 1-1; Raudsepp-Hearne et al., 2010). Regulating services modulate the flow and cycle of systems that have an overarching impact on the conditions of Earth, such as carbon sequestration and water purification. Supporting services enable the basic conditions required for other services, such as nutrient cycling and soil formation. Provisioning services are the materials and energy that are directly consumed, such as food and hydropower. Cultural services are the intangible benefits such as spiritual or educational values derived from contact with nature.

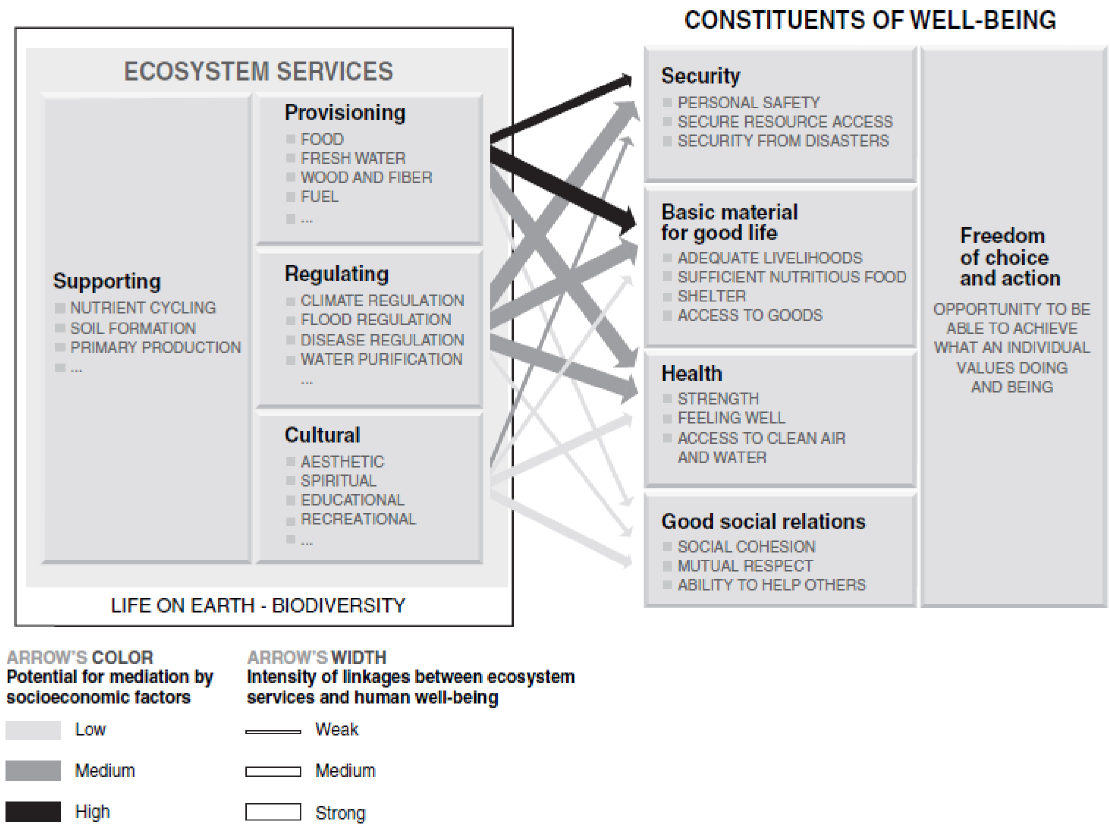

Figure 1.1 Linkages between ecosystem services and human wellbeing (MEA, 2003)

Ecosystem services contribute to many different aspects of human wellbeing (MEA, 2003), including in the areas of security, materials, health, and social relations (Figure 1.1). Security includes personal safety, both direct and indirect through access to resources and shelter from the elements. Material wellbeing encompasses the food and goods that support human survival and livelihoods. Health includes basic necessities like clean air and water that support strength and wellness. Social relations are the aspects that bring people together such as shared values or shared adversity.

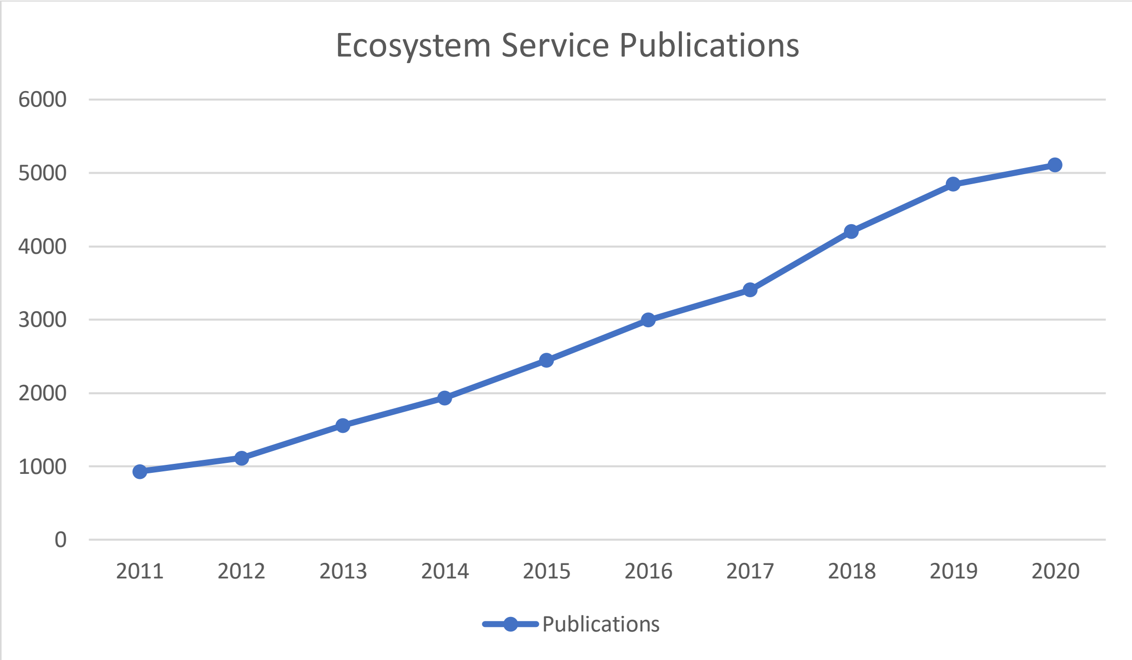

Figure 1.2. A graph of Web of Science indexed ecosystem service publications from 2011-2020.

As evidenced in the literature, the ecosystem service concept has wide acceptance. A Web of Science topic search for "ecosystem service*" reveals the history of ecosystem service publications starting in 1983 through the present day. In the 10-year period from 2011 to 2020, annual publications have gone from less than1,000 to more than 5,000 and increased at an average annual rate of more than 450 publications per year (Figure 1.2).

Critiques of the concept include the monetization of nature, ambiguity of classification, and the implications of simplified modeling (M. Schröter et al., 2014). The ambiguity of the classification system can result in over- or under-counting ecosystem services and an inherent perception that these services are distinct and separable. The complexity of ecosystem service dynamics can lead to a need for simplified modeling due to analytical constraints. As the ecosystem services framework has matured and become more widely used there are at the same time concerns about the robustness of ecosystem service data and analysis methods. While these critiques are valid, the focus of this thesis is the implications of the technical solution to ecosystem service assessment on science, science-policy implementation interface, and education.

1.3.2 Ecosystem Service Assessment Methods and Tools

Ecosystem service assessments depend on integrating multiple methods and diverse datasets (Harrison et al., 2018). Methods commonly used to conduct ecosystem service assessment include supply modeling (Zulian et al., 2018), time use studies (García-Llorente et al., 2016), and value transfer (Johnston et al., 2015). Data used in such assessments can include large existing datasets created for other purposes using technologies such as remote sensing, as well as field data collected expressly for an analysis. This multiplicity of methods and data creates challenges for assessment.

Ecosystem service assessments are complex and can rarely be completed with a single method. Working within constraints to meet the possibly incompatible supply and demand requirements of multiple ecosystem services requires an encompassing approach. Multiple methods and tools are used to (Dunford et al., 2018):

- Evaluate multiple ecosystem services,
- Calculate their supply and demand,
- Accommodate a variety of data,
- Adapt to multiple priorities,
- Compensate for methodological gaps with complementary methods, and
- Meet specific targets.

Each of the above points contribute to ecosystem service assessments in specific ways. Concurrent evaluation of multiple ecosystem services informs the understanding of interdependent dynamics in a study area. Calculating the supply and demand of ecosystem services establishes thresholds for target levels of services. Accommodating a variety of data types allows for the integration of multiple kinds of information to produce a more complete picture of target ecosystem services and their importance. Use of multiple methods supports analysis of the interplay among oppositional or mutually reinforcing priorities for ecosystem services benefits. Gaps within and between methods can be filled through the aggregation of methods. The sensitivity and specificity of methods may require multiple approaches.

Method integration for ecosystem service assessment is accomplished by (Harrison et al., 2018):

- The creation of input-output chains,
- Evaluation and iteration on results,
- Customization and development of tools, and
- Optimization approximation.

These concepts are applied manually using GIS, statistical packages, and programming, or through other specialized software. There are advantages to using ecosystem service software instead of performing a manual analysis. Primarily, the advantages are ease of use and defensibility due to standardization and reproducibility of results. Some of the software are generalized, covering many different ecosystem services, while others are more specific. Some software emphasize precision and have high data requirements, while others emphasize magnitude and require less data. There have been multiple comparisons of spatially-explicit ecosystem service assessment tools (Bagstad et al., 2013; S. L. R. Wood et al., 2018). Common assessment tools include InVEST (Nelson et al., 2009), SOLVES (Sherrouse et al., 2011) and ARIES (Villa et al., 2014), which use relatively simple models. The resources required for more complex analysis are often too substantial to evaluate multiple ecosystem services simultaneously.

In this section, I focus on the specific software of InVEST, SWAT, and SDM and, more generally, on open spatial data processing. InVEST is in wide use and, with low data requirements, covers many ecosystem services (Kareiva et al., 2011), which makes it easy to apply broadly (Figure 1.3). SWAT, which has high data requirements, is widely used by hydrologists to model the interactions between soil and water (Arnold et al., 2009). SWAT is also increasingly used in ecosystem service assessments to evaluate water related services *(*Figure 1.4*)*. Species distribution modeling (SDM) is used by biologists to predict the expected distribution of animal populations (Timoner et al., 2021)and it has implications for the provisioning and support of ecosystem services (Figure 1.5). SDM has data requirements that vary with each specific statistical method and desired certainty. Open spatial data processing allows for the coordinated distribution of spatial data and software through standardized protocols (Giuliani, Lacroix, et al., 2017). One set of protocols is developed by the Open Geospatial Consortium as their Web Service (OWS) standards (Baumann, 2012; Mueller & Pross, 2015; Schut, 2010; Vretanos, 2014).

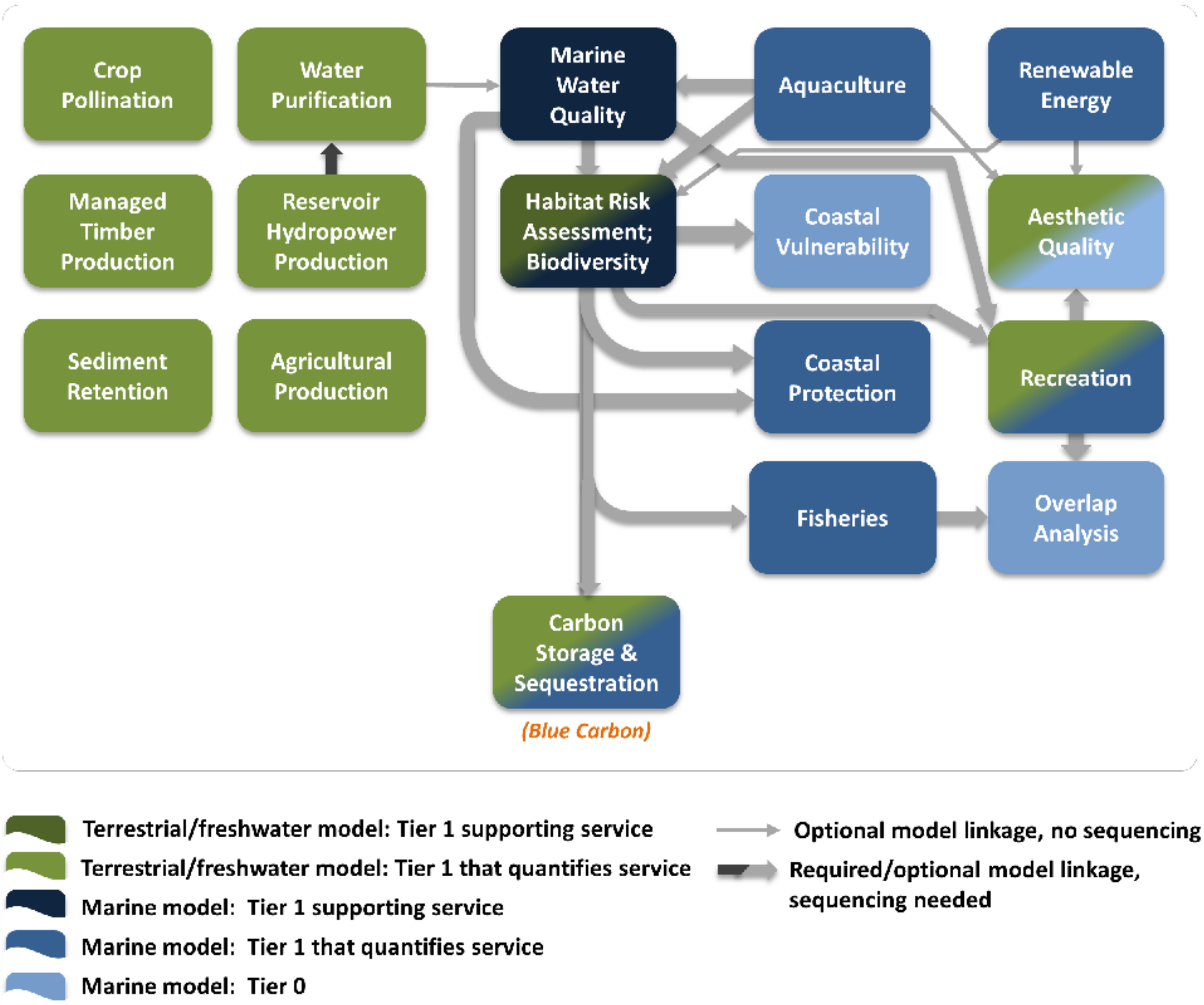

Figure 1.3 Overview of InVEST suite of models (Natural Capital Project, 2017)

In 2018, Wood et al. identified twelve ecosystem service tools, comparing them based on ease of use and modeling capabilities across the ecosystem service categories of provisioning, regulating, supporting, and cultural services. The Artificial Intelligence for Ecosystem Services (ARIES; Villa et al., 2014) and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST; Nelson et al., 2009) stand out as covering the most ecosystem services, while InVEST is considered the easier of the two to use.

InVEST has the additional advantage of being free and open source and, therefore in addition to being available for use by all, its functionality can also be examined and modified by anyone. Created by the Natural Capital Project (https://naturalcapitalproject.org), InVEST formalizes a systematic approach to ecosystem service assessment (Figure 1.3). It consists of more than twenty ecosystem service models and supporting software tailored for specific applications, including the Resource Investment Optimization System (RIOS; Vogl et al., 2017) for watershed management and the Offset Portfolio Analyzer and Locator (OPAL; Mandle et al., 2016) for impacts of restoration. InVEST can deliver these with low data requirements and high transparency, thus enabling the comparison of scenarios based on magnitude of results rather than precision. Such an approach supports timely and effective allocation of computing and human resources. Results can be used to quickly evaluate scenarios and highlight when and where more in-depth analyses could be valuable. Ecosystem service assessment can also be performed by repurposing software like SWAT, depending on the availability of data and the desired analytical precision.

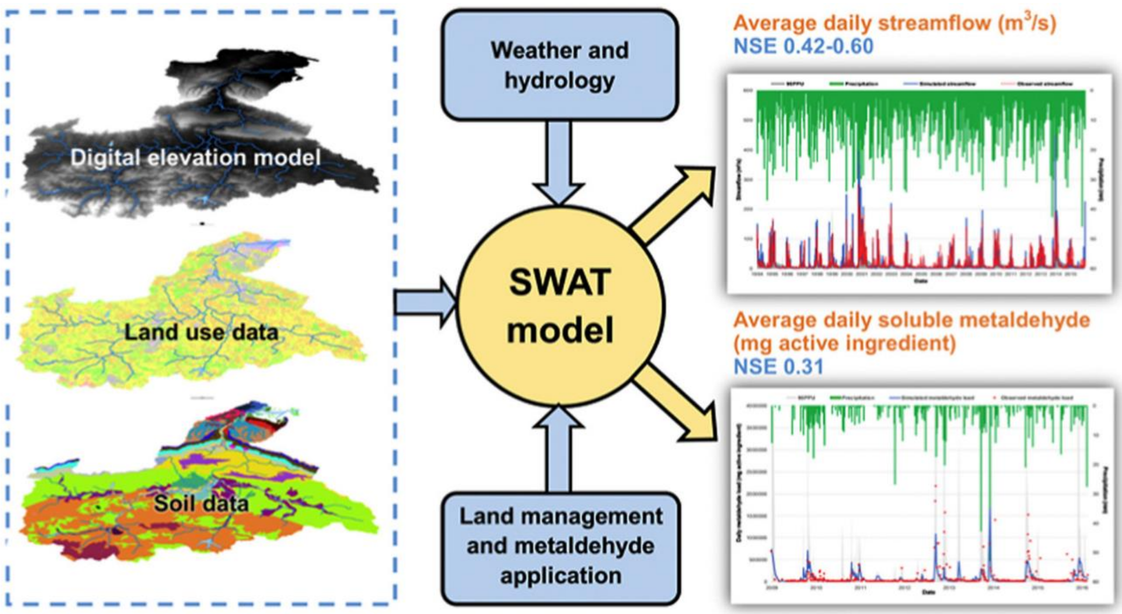

Figure 1.4 Overview of SWAT (Purnell et al., 2020)

SWAT, a watershed modeling tool (Vigerstol & Aukema, 2011), has been proposed as a mechanism to quantify ecosystem services. Francesconi et al. (2016) conducted a literature review to identify studies in which SWAT was explicitly used for quantifying ecosystem services in terms of its provisioning, regulating, supporting, and cultural aspects. A total of 44 peer reviewed publications were identified. Most of these used SWAT to quantify provisioning services (34%), regulating services (27%), or a combination of both (25%). Studies using SWAT for evaluating ecosystem services are limited (approximately 1% of SWAT's peered reviewed publications). However, the available body of literature sets the stage for SWAT to be used for quantifying ecosystem services to assist in decision-making (Lehmann et al., 2019).

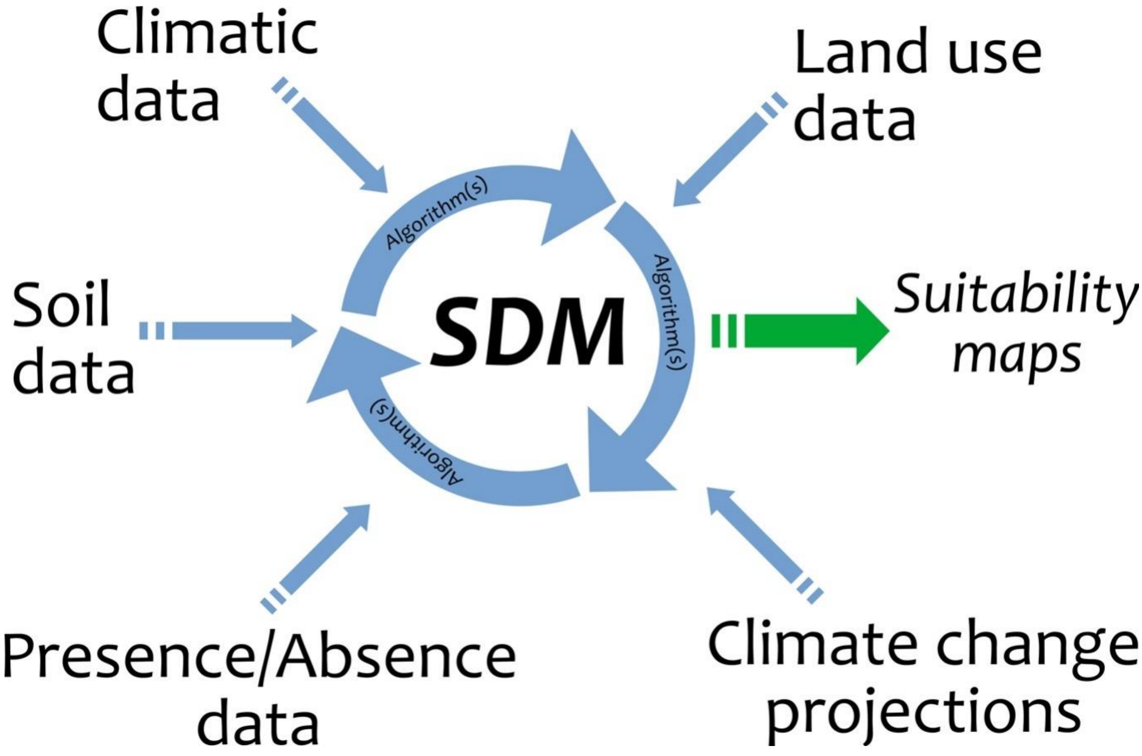

Figure 1.5 Overview of SDM (Pecchi et al., 2019)

Ecosystem services often depend on the distribution of biodiversity (Tscharntke et al., 2012). One method for SDM is the generalized regression analysis and spatial prediction (GRASP), which produces spatial predictions using generalized regression analysis, establishing a relationship between response variables and spatial predictors (Lehmann et al., 2002; Maggini et al., 2014). Rigorous methods are needed for integrating and generalizing spatial predictions. Many ecosystem characteristics have been measured and predicted. GRASP calculates the statistical relationship between variables, providing a method for spatial predictions using point measurements

(Lehmann et al., 2002; Maggini et al., 2006). New packages are now being used to streamline the SDM process such as Biomod (Thuiller et al., 2009) or Maxent (Elith et al., 2011). These methods have been compared in Elith et al. (2006).

1.3.3 Workflows

The workflow for transitioning from data collection to decision making is always complex. The creation of protocols for finding and accessing data is the first step. Methods are then needed to transform data into information. Analysis is needed to transform information into knowledge. Policy is needed to transform knowledge into action. In an ecosystem service assessment these transitions require access to data and assessment software, infrastructure for producing and analyzing information, methods for evaluating and disseminating knowledge, and dialogue to create policy that demonstrates understanding.

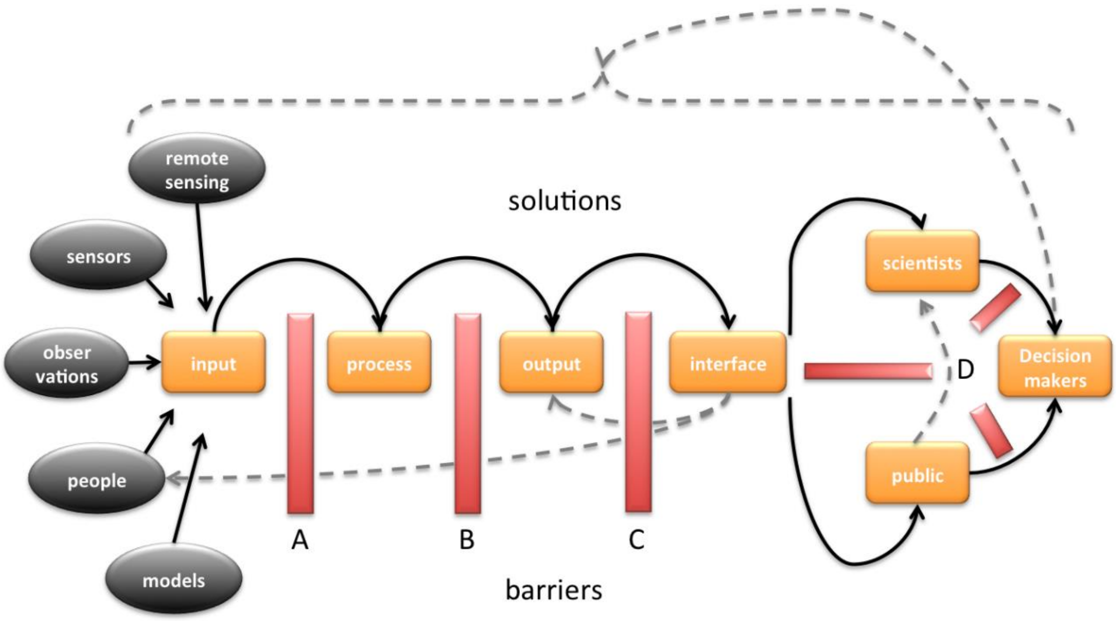

Figure 1.6 Barriers and solutions in the workflow from data to decision making. (A) data access; (B) information production; (C) knowledge acquisition; and (D) scientific communication. Plain arrows represent solutions to lift barriers and dotted arrows represent active feedback in the workflow. (Lehmann et al., 2017)

The transition from data to decision making can be impeded by four barriers (Figure 1.6):

- Data access,
- Information production,
- Knowledge acquisition, and
- Scientific communication.

Barriers to data access can come from the absence of data, scarcity, use restrictions, or format issues. The use of spatial data infrastructure (SDI) to manage data and provide access through standards like the OGC Web Services (OWS) can greatly improve access (Giuliani et al., 2011). The enviroGRIDS project (Lehmann et al., 2015) exemplified good data sharing practices in its land use change and hydrological modeling in the Black Sea catchment. In this project they were able to predict future water resource vulnerabilities (Bär et al., 2015) and scarcity (Fasel et al., 2016). The outputs of the project were made available through a GeoNode SDI (http://blacksea.grid.unep.ch) using OGC standards. This contrasts with many other projects where outputs are difficult to find and use.

Other projects address similar issues of data and metadata access and integration. The Global Earth Observation System of Systems (GEOSS; Giuliani et al. 2011) and the European framework INSPIRE use SDI to greatly improves the availability of and access to data for dissemination and use in new projects. Projects are conducted at a variety of scales, from local to global. Worldwide projects include the Global Risk Data Platform (http://preview.grid.unep.ch; Giuliani & Peduzzi, 2011) and the Committee on Earth Observation Satellites (CEOS) International Directory Network (https://idn.ceos.org; IDN), the latter of which contains more than 27,000 datasets and service descriptions. In June 2020, the latter, formerly known as the Global Change Master Directory (GCMD), was depreciated but because it used open standards it was easily merged into a new directory (NASA, 2020), highlighting the value of using open standards. It is exactly this ability to readily reuse data and processes that has great promise for making better use of existing resources and fostering novel analysis.

Barriers to information production can be a challenge for analysis. In Hansen et al. (2013), the authors present a global 30 meter resolution map of forest change from 2000 to 2012 (http://earthenginepartners.appspot.com/science-2013-global-forest). The results represent a time series analysis of 654,178 Landsat 7 ETM+ images with a total of approximately 20 trillion pixels. This is a substantial amount of data that would be difficult to process with a desktop computer. Instead, the forest change map was created using Google Earth Engine because it has a sophisticated API and extensive computational resources including an integrated data catalog with Landsat 7 imagery. The analysis of large datasets is increasingly commonplace, but the resources required to do such fine scale analysis are too large for most individuals, driving them to analysis platforms. Other studies with Google Earth Engine have looked at crop mapping (Shelestov et al., 2017), urban growth (Patel et al., 2015), and wetland extent (Alonso et al., 2016).

The evolution of high-performance computing in the cloud enables solutions like Google Earth Engine. The big data revolution has driven the continuous development of these technologies. Similar services, such as ArcGIS Online and GIS Cloud, offer competing solutions to Google Earth Engine (Evangelidis et al., 2014). The transition of such analyses to cloud based platforms provides scalability that few individuals could achieve with their own resources. It is specifically the scalability of web-based services that provides a solution to difficult or otherwise unsolvable information production problems.

Knowledge acquisition is challenging, but an API provides a foundation to build on. One sophisticated API offering is the Berkeley Ecoinformatics Engine (https://ecoengine.berkeley.edu/). It facilitates the exploration, visualization, and analysis of an extensive collection of biological and geospatial information. The API drives the creation of custom visualizations and analysis, and it serves as a prime example of the reason to provide an open API. This provides researchers, citizen scientists, and students with the building blocks for novel use without requiring the creation of their own system or a precise understanding of how the components function.

The publication of APIs is becoming more common. For example, the FAOdata API (http://api.data.fao.org/1.0/index.html) is offered by the UN Food and Agriculture Organization (FAO); the GEO DAB API (http://api.eurogeoss-broker.eu/) is offered by the Group on Earth Observation (GEO); and the NASA API portal (https://api.nasa.gov/) is offered by NASA.

Scientific communication is essential for rigor, which is validated through peer review. SeaSketch was designed as a participatory web-based tool for marine reserves. Formerly known as MarineMap, SeaSketch was used by stakeholders of California's Marine Life Protection Initiative (Merrifield et al., 2013). This tool facilitated a public process by engaging external stakeholders, but also provided a platform which gave scientists tools to better communicate local geography and debate science-based guidelines.

Using new technologies, the production and distribution of information and knowledge can be better managed to address pressing environmental challenges. Spatial data infrastructure can facilitate this through a more streamlined approach for innovation. Web services can increase data access and improve methods with standardized metadata and APIs. Financial resources are needed to maintain scalable tools for end users, but the use of standards reduces costs and simplifies maintenance as demonstrated by the depreciation and merger of GCMD into the IDN.

1.3.4 Reproducibility

The "reproducibility crisis" in science, in general, and in geographic information science (GIScience), in particular (Nüst et al., 2018) has been acknowledged. As noted in Section 3.1, reproducibility is a complex problem involving legal barriers (Borgman, 2012), technical barriers, business models (Doctorow, 2019), and academic reward mechanisms (Nüst et al., 2018). Here, I focus on aspects of reproducibility that are amenable to improvement through interoperability.

1.3.4.1 Reproducibility in science

Broadly speaking, reproducibility is the capacity to replicate the results of a scientific study. However, there are varying definitions of reproducibility in science (Nüst et al., 2018). For the purposes of this thesis, reproducibility is the ability to gather the same inputs and produce the same outputs. This is important because it demonstrates that results are reliable. If another scientist can achieve the same success or failure, that reaffirms the data upon which conclusions are based. This inherently requires transparency and, ideally, is shared through a peer review process during which an in-depth inspection takes place. Actively ensuring reproducibility through detailed documentation can be time consuming but is recognized as a best practice for scientific work (Fehr et al., 2016; Stodden et al., 2016). In addition to improving the original researcher's understanding of the process needed to achieve desired results, it also benefits the scientific community through scalable mentoring and the sharing of knowledge needed to expand upon the work.

1.3.4.2 Irreproducibility in science

A 2016 survey of 1,576 researchers revealed that 52 percent believe there is a significant reproducibility crisis, 38 percent believe there is a slight crisis (Baker, 2016).

> "More than 70% of researchers have tried and failed to reproduce another scientist's experiments, and more than half have failed to reproduce their own experiments" (Baker, 2016, p. 452).

While there is increasing awareness about the need for improved reproducibility, there is clearly a shocking amount of room for improvement.

Irreproducibility is not caused by scientific misconduct except in rare cases (Collins & Tabak, 2014). Therefore, irreproducibility is not the result of bad actors but, rather, other aspects. These could be attributed to planning, analysis, or the culture of science, but are often the result of several sources. Responses to the survey conducted by Baker (2016) highlight the following 10 factors that contribute to irreproducibility, with more than 60 percent agreeing that these contribute at least some of the time:

- Selective reporting
- Pressure to publish
- Low statistical power or poor analysis
- Not replicated enough in original lab
- Insufficient oversight/mentoring
- Methods or code unavailable
- Poor experimental design
- Raw data not available from original lab
- Fraud

- Insufficient peer review

Several authors identified experimental design, pressure to publish, and few venues to detail failures as contributing factors to irreproducibility (Baker, 2016; Collins & Tabak, 2014). One respondent in Baker (2016) estimated the overhead cost of ensuring reproducibility at 30 percent and likened it to brushing ones teeth by saying,

> "It is good for you, but it takes time and effort. Once you learn it, it becomes a habit." (Baker, 2016, p. 454).

This comment cheekily conveys that ensuring reproducibility can be tedious, but once it becomes a routine it yields real benefits.

1.3.4.3 Improving reproducibility

There are numerous approaches to improving reproducibility (Chawanda et al., 2020; Kedron et al., 2020; Nüst & Pebesma, 2020). One of the easiest ways is for a researcher to simply ask a colleague to reproduce the work from experimentation notes (Baker, 2016). However, this is just a beginning, as it can still promote the creation of data and expertise silos and, therefore, a broader approach is necessary. Baker (2016) found that in the previous five years, concrete steps to improve reproducibility had been taken in the labs of one-third of respondents.

Literature details the key role that interoperability plays in reproducibility. This is particularly evident with data management topics, especially access, authorized use, and reliability. The ability to use open standards to access data with open licenses or minimum restrictions can be established through personal, journal, and institutional policies that make discovery easier by favoring short or no embargoes on sharing and actively publishing data in catalogs. As an added benefit, this can also make research more visible, thereby increasing citations and producing higher rewards for researchers who choose to engage in these practices. Using open standards to do this typically requires servers to accommodate open standards; this has added benefits which can make working easier, such as infrastructure to create backups and archives and scalable computer and network resources. The use of open standards can also reduce difficulties in reading data and interpreting values through the application of data and metadata standards.

1.3.5 Reproducibility in GIScience

The breadth of science makes generalizing about reproducibility difficult. In GIScience, the underlying aspects of space impart a certain commonality. This makes challenges of reproducibility easier to categorize and address. Nüst et al. (2018) created a reproducibility classification system for geospatial analyses that they used to evaluate nominations for best full or short papers in the periods 2010 and 2012 to 2017 submitted to the Association of Geographic Information Laboratories in Europe (AGILE) conference series. The classification system singles out 5 areas of reproducibility:

- input data;
- preprocessing;
- methods/analysis/processing;
- computational environment; and
- results.

These were each evaluated as unavailable, documented, available, or available with an open license and permanent URL. The analysis of papers included a survey of authors, which found that most respondents at least partially agreed with the evaluation of their papers as having low reproducibility while also indicating they thought reproducibility was important. Among the barriers mentioned, "several respondents noted a lack of supporting tools as a main impediment for reproducibility" (Nüst et al., 2018, p. 14), as well as lack of time. Interoperability offers at least a partial solution. Lack of time and lack of software are closely related and an abundance of one may compensate for a lack of the other. Improvements in software could produce easily shared workflows that would increase the ratio of reward to effort by reducing the time and expertise needed to examine a study in detail and reproduce it.

1.3.6 Interoperability

Lack of interoperability represents a significant challenge to the ability to conduct ecosystem service assessments. Interoperability is, "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" (IEEE, 1991, p. 114). Interoperability is not a single measurable characteristic, but rather comprises several aspects ranging from design to purpose

(Giuliani et al., 2019). For the purposes of this thesis, interoperability is defined as the ability to exchange and make use of data and models between software components on a single computer or across a network. In a practical sense, this means being able to readily link different ecosystem service models as well as share and collaborate with minimal barriers. In the absence of interoperability data can be locked behind insurmountable barriers, models can be rendered unusable, and results siloed.

I explore the lack of interoperability and its implications for ecosystem service assessments throughout the thesis. Additionally, I discuss how interoperability enhances assessments through streamlined workflows.

Design, as it pertains to interoperability, is a function of the specific technologies in use and how they are applied. Purpose consists of how ideas are expressed and relate to each other. Interoperability can then be categorized into four levels of integration, depending on design and purpose (Giuliani et al., 2019):

- Same design and same purpose;
- Same design but different purpose;
- Different design but same purpose; and
- Different design and different purpose.

Systems with the same design and same purpose use identical technologies and apply them in equivalent ways. They contain similar kinds of information, expressed in comparable terms. These systems are the most interoperable. Systems with the same design but different purposes use identical technologies and apply them in equivalent ways. However, they contain different types of information and may express them in incomparable terms. Such systems are interoperable, but it may not be useful to use the information from one system with the other. Systems with different designs but the same purpose use distinct technologies. However, they do contain similar kinds of information expressed in comparable terms. Such systems are not interoperable, but it may be possible to use the information from one system with the other if that information is transferred out of the system. Systems with different designs and different purposes use distinct technologies. They contain different types of information and may express them in incomparable terms. Such systems are not interoperable, and it may not be useful to use the information from one system with the other.

Interoperability has the potential to address several technical challenges for ecosystem service assessments. These include increased access to data (Giuliani, Nativi, et al., 2017), improved integration of multiple methods (Dunford et al., 2018), and streamlined sharing and publication of results (Nüst et al., 2018). These are important because they are the beginning, middle, and end to a workflow and, when interoperable, streamline assessments. Through the detailed sharing of data, methods, and results, sufficient information can be conveyed to inform others and enable reproduction of an ecosystem service assessment. The approach to this is my original contribution, detailed in this thesis.

1.3.7 Web Services

The Open Geospatial Consortium (OGC) Web Services (OWS) represents a major milestone for spatial data interoperability because they define a set of standards for exchanging geographic data that preserve ontological representation. The Open Geospatial Consortium (OGC) created four standards of particular interest:

- Table Joining Services (TJS; P. Schut, 2010) for tabular data,
- Web Coverage Service (WCS; Baumann, 2012) for raster data,
- Web Feature Service (WFS; Vretanos, 2014) for vector data, and
- Web Processing Service (WPS; Mueller & Pross, 2015) for geoprocessing.

OGC standards go far beyond the transfer of static data to include real time access to sensor networks, metasearch of data aggregators, and even data management for computation between models on a single computer or distributed across a network (Giuliani et al., 2012). OGC standards do not have accompanying implementations in software but rather contain application programming interfaces (APIs), functionally a vocabulary and grammar for the transfer and processing of spatial data. This means that spatial data are not stored, queried, and retrieved without an understanding of their inherent qualities, as is typically the case with the File Transfer Protocol (FTP). Instead, spatial primitives equivalent to equality, subtraction, and division, among others, can be used to remotely interact with the data before transferring with OWS. The significance of this is that it provides both the unified communication protocols by which people can interact with data, and the mechanism for machine-to-machine communication. In effect, OWS are analogous to a universal language for spatial data.

These OGC standards specify the use of the Hypertext Transfer Protocol (HTTP) to communicate metadata and data inside of Extensible Markup Language (XML) documents. The metadata includes basic data like extent, projection, and provenance essential for data quality (Zhang et al., 2020), and the availability of basic query functions with parameters like counts and the list of names and types for datasets or processing functions. The data can be embedded directly in an XML response document but is more typically given by reference to an external data source that can be in a variety of formats. Although HTTP and XML may be unfamiliar to some, they are mature fundamental technologies for the Internet with extensive software libraries and documentation.

The use of OWS in the environmental sciences is arguably well established as exemplified in the Global Earth Observation System of Systems (GEOSS; https://www.earthobservations.org/geoss.php), Infrastructure for Spatial Information in the European Community (INSPIRE; https://inspire.ec.europa.eu/), and the Global Framework for Climate Services (GFCS; https://gfcs.wmo.int/), among other initiatives (Giuliani, Nativi, et al., 2017). However, these emphasize data services and are mostly used to discover or publish data at the beginning or end of analysis, and the intermediate steps of the analysis workflow are typically done without OWS. This represents a break in what could otherwise be a cohesive interoperable workflow and it inherently silos data and methods.

The ability to link processes across models and platforms throughout a workflow can be achieved with the creation of corresponding WPSs (Castronova et al., 2013). This is a nontrivial task, as reflected by its low adoption rate. This is likely because the solutions for OWS are fragmented. There is no official OGC implementation and no alternatives that support all four of the TJS, WCS, WFS, and WPS standards. While individually each OWS provides interoperability advantages, the maximum potential can be achieved when used in concert. Therefore, the challenge is to integrate TJS, WCS, WFS, and WPS for a generalized end-to-end solution that could be widely used for ecosystem service assessment.

1.4 Structure of the Thesis

This thesis follows the three-article format and is structured into six chapters. The three manuscripts and the chapters within which they are embedded help to answer the research questions defined in Section 1.2, and complemented by the list of research papers in Section 2.5.2.

Chapter 1 (Introduction and Theoretical Framework) has introduced the Sustainable Development Goals, ecosystem services assessment creation and reproduction (Section 1.1), and then continued with a summary of the research problem and questions (Section 1.2). Section 1.3 (Theoretical Framework) expands on the foundation of ecosystem services and web services, explores information barriers for going from data to decision making, introduces interoperability, and covers reproducibility across scientific disciplines with an emphasis on GIScience.

Chapter 2 (Data and Methodological Approach) provides details on the ecosystem service assessment process along with lessons learned from three case studies (Section 2.1), provides an overview of the Open Geospatial Consortium Web Service (OWS) standards for geospatial data and model parameters (Section 2.2), and covers the inclusion and significance of these standards in Spatial Data Infrastructure (SDI: Section 2.3), their roles in the SWATCH21 project, and how this calls for an Ecosystem Service Web Service (ESWS)-like solution (Section 2.4). Chapter 2 concludes by acknowledging the projects that supported this work and providing substantive information on seven papers I co-authored, which serve as important foundations for the development of ESWS (2.5).

Chapter 3 presents the first of the three articles that are important outcomes of my research. Published in *Computers and Geosciences* “A framework for ecosystem service assessment using GIS interoperability standards” details an application of open web standards to ecosystem service assessment to facilitate creation, iteration, and dissemination in a seamless way (Lacayo et al., 2021).

Chapter 2 is composed of the second article, which has been submitted to *Ecosystem Services.* “Designing lasting ecosystem services assessment tools for the science-policy implementation interface” makes the case for applying open web standards to enhance the science-policy implementation interface for ecosystem services assessments (Lacayo et al., under consideration).

Chapter 5 offers the third article in this three-article format thesis. In development for submission to *Environmental Modeling & Assessment* or similar journal, “Extending the benefits of ecosystem services web services (ESWS) to education” (Lacayo and Lehmann, in development) builds on the experience of the Coursera massive open online course (MOOC) on ecosystems services, for which I developed the GIS tutorial, and the ecosystem services game (agriculture edition) that I adapted for online distribution. Based on these and other examples of successful ‘serious games’, the article examines the value of ESWS as an educational tool that could minimize hardware and set up demands on students, allowing them to focus on developing transferrable analytical skills.

Chapter 6 discusses how the ESWS provides answers to the research questions posed in Chapter 1, how its modularity provides a mechanism for expansion, and discusses third-party integrations, limitations, and recommendations. Finally, the thesis concludes with a summary of the key findings.

2. DATA AND METHODOLOGICAL APPROACH

In this chapter, I describe the methodological foundation for ESWS. I begin with a discussion of three ecosystem service assessments, their methods, and lessons learned that inform the design of the ESWS followed by an overview of ecosystem service assessment tools and their use in this thesis. I follow with details on web service standards and a discussion of existing spatial data infrastructure that are critical for this work. I conclude with a discussion of the SWATCH21 project and how it informs the core of this thesis.

2.1 Ecosystem Service Assessments

There are many different kinds of ecosystem service assessments (Bateman et al., 2013) and tools. The methods and level of detail of each of these studies varies significantly. Examining specific ecosystem service assessments reveals details that get lost in aggregate. In Sections 3.1.1 to 3.1.3, I will discuss three studies with different geographic contexts and ecosystem services in which I was involved in varying capacities. First, in 3.1.1 I will discuss a regional study of water yield in China for which I was a technical advisor. In 3.1.2, I will discuss a study of coastal protection in the United States, where I was a GIS analyst. In 3.1.3, I will discuss a study of worldwide recreation and tourism, for which I was a software developer. Each of these studies demonstrates in a different geographic context the essential value of ecosystem service assessments and the challenges of analysis.

2.1.1 Water yield in China

An assessment of water yield was conducted to further understanding of flooding in a semi-arid region of China and identify opportunities to attenuate it (Section 3.1.1). The assessment modeled the hydrologic system with a water balance model, dividing precipitation into groundwater recharge, transpiration, and evaporation, leaving the balance as water yield (Li et al., 2018). The analysis clearly demonstrated that an increase in development and accompanying impermeable surfaces led to an increase in water yield and, consequently, flooding events. This was the predictable outcome of loss of vegetation and landscapes that would normally absorb and slow down the flow of water. Of particular value in this setting, the ecosystem service assessment could be used to model how to optimize future development and restoration efforts with an understanding of impacts on water yield, minimizing the frequency and magnitude of flooding events.

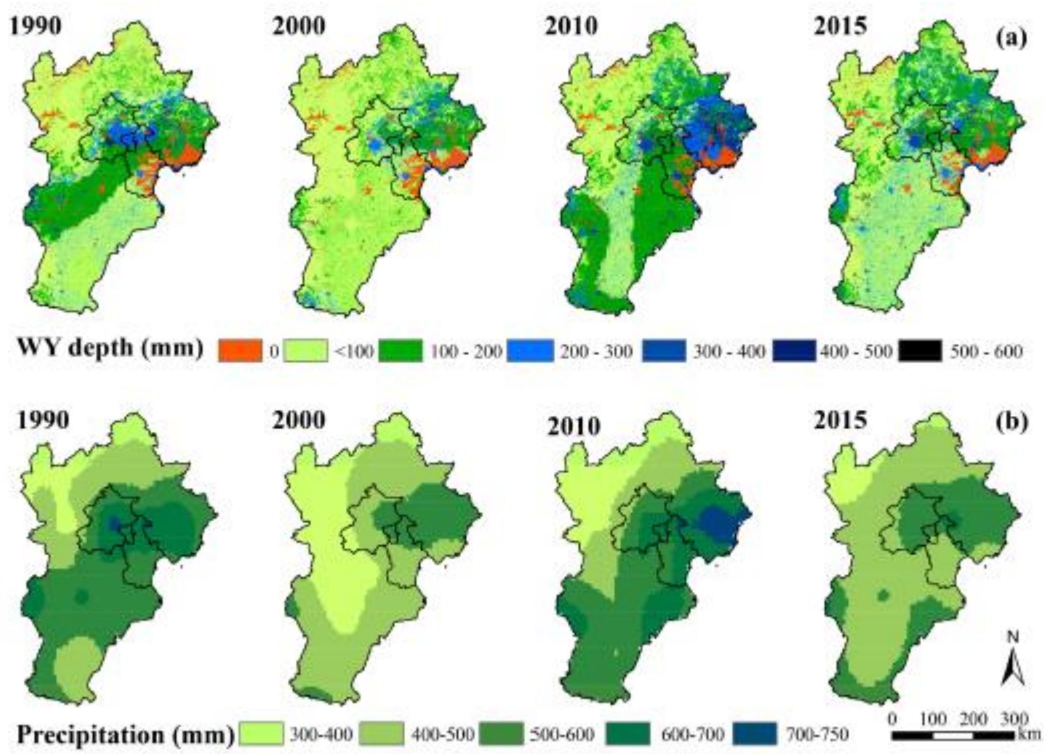

Figure 2.1 Spatial and temporal distribution of (a) water yield and (b) precipitation (Li et al., 2018)

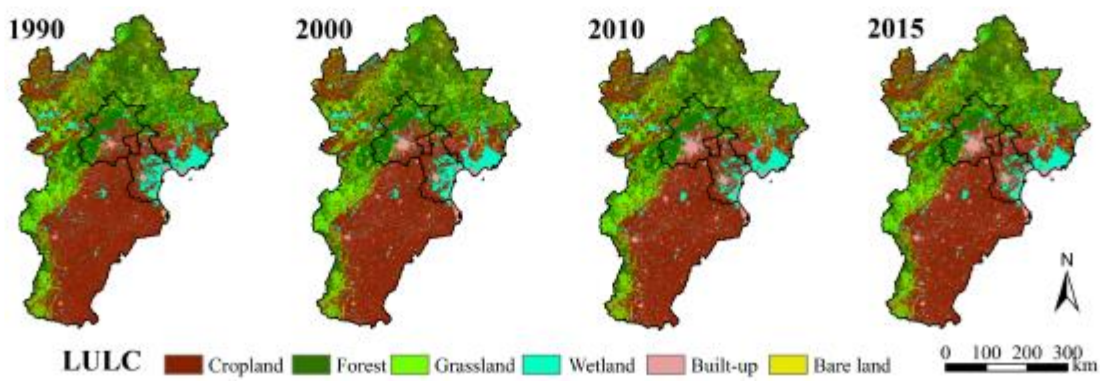

Figure 2.2 Change in LULC (Li et al., 2018)

In Li et al. (2018) InVEST was used to find that from 1990 to 2015, water yield in the Beijing-Tianjin-Hebei region increased by 1,047 million cubic meters (5.1 %) (Figure 2.1) as built up areas increased by 35% (Figure 2.2). This semi-arid region is approximately 215,000 km^2, with a population of more than 110 million people. This change in water yield reflects the reduction in ecological buffers that slow down the flow of water and in their absence cause an increase in flooding events.

The analysis had many challenges. Metadata for models and data requirements were especially challenging. The format of tables for biophysical data was not completely clear in the model documentation. The localization of files, particularly differences in decimal separators in tabular data, was a source of error. Differences in source data projections from changes in official projections and different providers proved difficult. The requirement to use a projection with linear units but no obvious warning message was a tripping point. Confusing reprojection with set projection tools during preprocessing caused errors. Model warnings that projections may not be equivalent because of rounding errors and label variations were unclear. Interpreting outputs like the water yield of a lake having a value of zero was confusing at times.

Based on almost two decades of GIS experience and more than a decade of teaching, I know that these mistakes are easy to make and very common. InVEST is a widely used tool for ecosystem service assessment and has a low barrier to adoption but does require pre- and post-processing skills that are often overlooked. These errors are, in principle, data format issues, metadata oversights, basic GIS skills, and interpretation issues. Additional data validation procedures in InVEST could have prevented some of these challenges but the use of web services could better address this. TJS, WCS, and WFS web services could have streamlined the data input process with the elimination of data format issues including variations in equivalent projections. WPS web services could have reduced data projection errors through its built-in data validation features.

2.1.2 Protective marine ecosystems in the United States

People and property are increasingly at great risk from coastal hazards due to climate change (Sallenger et al., 2012; Shepard et al., 2012). Intact reefs and coastal vegetation reduce the likelihood of losses and their magnitude (Day et al., 2007). Sea level rise and coastal flooding are expected to increase significantly (Pachauri & Reisinger, 2008), lending urgency to the need to act. Grey infrastructure is traditional, non-living built structures. These can offer necessary protection in some cases, but can further degrade the ecosystem (Defeo et al., 2009; Peterson & Lowe, 2009). On the other hand, green infrastructure is engineered living structures such as oyster beds or kelp forests that expand the ecosystem. Both grey and green infrastructure require knowledge for where to place them, but green infrastructure, as a living structure, also requires the conditions under which it can thrive (M. H. Ruckelshaus et al., 2016).

Assessment of coastal protection provided by marine ecology in the highly litigious United States offers an example of the potential importance of reproducibility. Arkema et al. (2013) conducted a detailed analysis of the protective effects of marine ecology, such as oyster beds and eel grass, to reduce incoming wave energy and storm surges. This makes the case for conservation of specific coastal areas. Results were particularly important given the power of development interests and the disproportionate effects on vulnerable populations. The dollar value of potentially impacted areas was modeled in the presence and absence of shielding ecosystems. Model results were used to suggest to policy makers that coastal development should be limited in specific areas for the greater good, despite the potential financial losses to private interests. Certainty in these results and the ability of another party to reproduce them could become material evidence in a legal dispute. Were this to arise, reproducibility would greatly enhance confidence in results of the assessment and their application to inform policy.

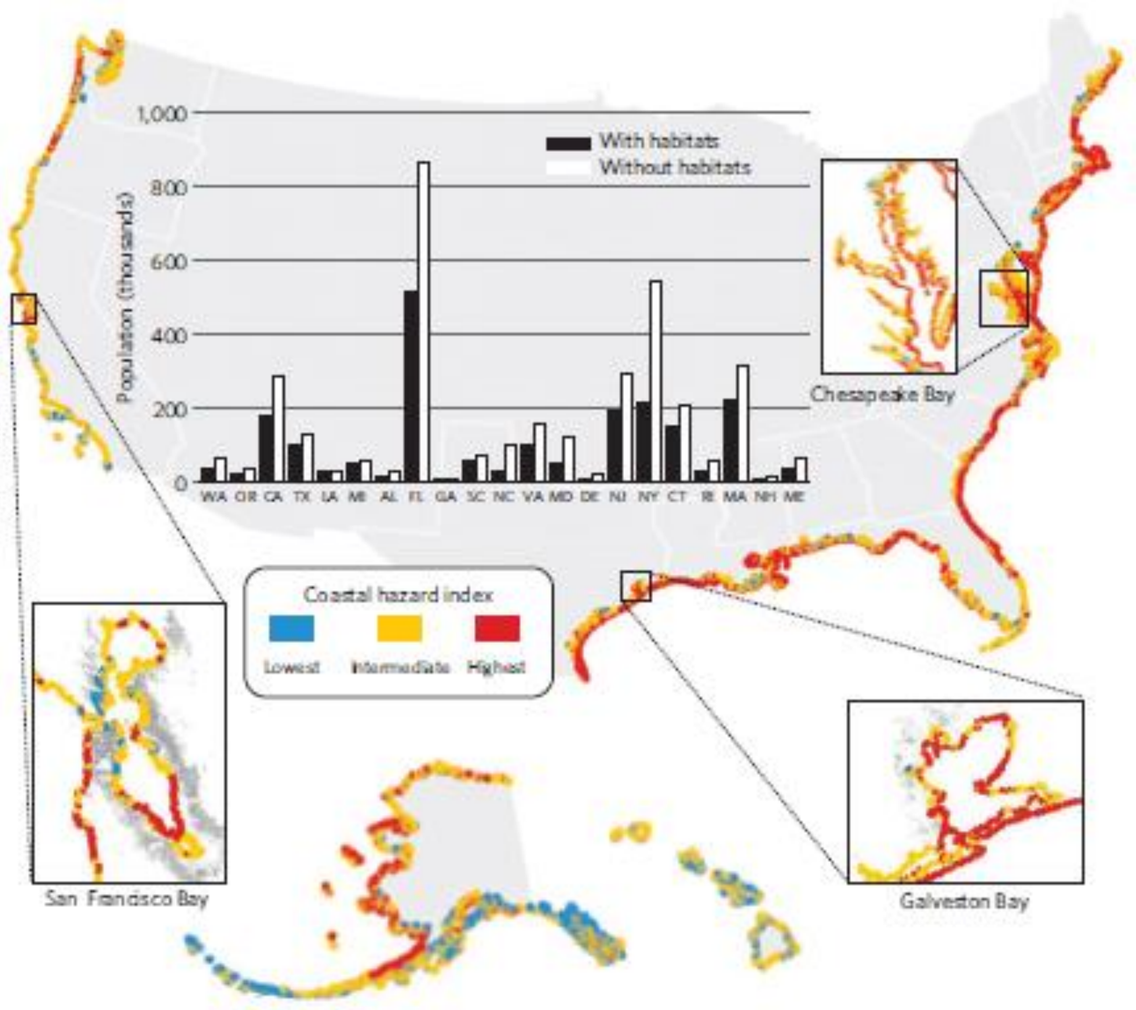

Figure 2.3 Exposure of the US coastline and coastal population to sea level rise in 2100 (Arkema et al., 2013)

In Arkema et al. (2013) a hazard index was calculated for the entire coastline of the United States at the square kilometer scale (Figure 2.3). This index incorporated the "protective role of ecosystems" (Arkema et al., 2013, p. 913) through an inventory of existing coastal ecology and a calculation of its moderating effect on storm surge and sea level rise. In the hypothetical absence of this protective effect, the difference in damages under different sea level rise scenarios was calculated. As technical staff for the study and co-author of the paper, I have firsthand knowledge of the study's analytical challenges.

The first challenge was the laborious work of visiting many different agency websites, both federal and state, downloading the correct data sets, and pre-processing them including necessary data sanitation. This required extensive manual processing. Attempting to perform the analysis with a single model revealed that the area was so big that it presented map projection distortion issues. As a result, the spatial extent of the study area had to be divided into several regions, each with their own model. This required additional human resources to debug the model to determine the source of errors, identify a practical solution, and implement that solution for the analysis. Ultimately, individual models had to be run for each region and then aggregated to obtain results for the final analysis.

More work is needed to identify where combining ecosystem-based and engineered approaches will be most effective for reducing damages (Arkema et al., 2013). However, expanding on the study would be difficult because of all the manual steps. Updating the inputs including the locations of different ecosystems, property values, and demographics would be challenging and time consuming. It has been nearly a decade since this work was completed. Ideally, it would be repeated, especially to assess demographic shifts and whether, as the study found, vulnerable populations continue to especially benefit from protective marine ecosystems. However, because of the manual fashion in which data were acquired and analyzed it would essentially have to be done from scratch. A streamlined workflow tool would have made this work much easier and in its absence this work is now abandoned.

2.1.3 Recreation proxy from social media for the globe

Tourism and recreation are important for economic and cultural reasons and, furthermore, provide wellbeing and other benefits (Martinez-Juarez et al., 2015). Data on tourism and recreational visits are usually obtained with site specific surveys or interviews. This can miss some types of tourism and be prohibitively expensive. In an age of social media, crowdsourcing can be a valuable source of data for ecosystem services assessments. However, acquisition and use of social media data present numerous challenges. It can be difficult to obtain because of website specific limits on access and use, while deriving meaningful information from the data can be challenging.

Using social media data, Wood et al. (2013) estimated recreation and tourism in the world (Figure 2.4). The study established the statistical relationship between the physical presence of Flickr users in the real world and empirical visitation data. The social media data consisted of the location and date of 200 million geotagged photographs and took than more than six months to gather. While licensing restrictions made sharing the social media data uncertain, others were able to use the data through a server-based model. With a graphical user interface (GUI), model users could perform a linear regression with the social media data by uploading the geographic data for the independent variables they selected. The server would then perform the required conversions and spatial aggregations to calculate the results. In this way, the social media data was made interoperable in spite of data licensing concerns and the “first study to ground-truth the use of data from social media to predict visitation rates” (S. A. Wood et al., 2013, p. 1) could be verified even while a critical dataset could not be shared. The interoperability of the model readily enabled verification and reproduction of the results without the need for the time, money, or expertise to regather the data. Furthermore, by establishing a dataset for dynamic data that social media users could change at any time by deleting their data an otherwise ephemeral data source was preserved and archived. Additionally, the approach in this study enabled other studies to use the model in their work and has resulted in more than 250 citations. Demonstrably, then, interoperability can not only alleviate some concerns around reproducibility, especially present with new methods, but can also facilitate productivity.

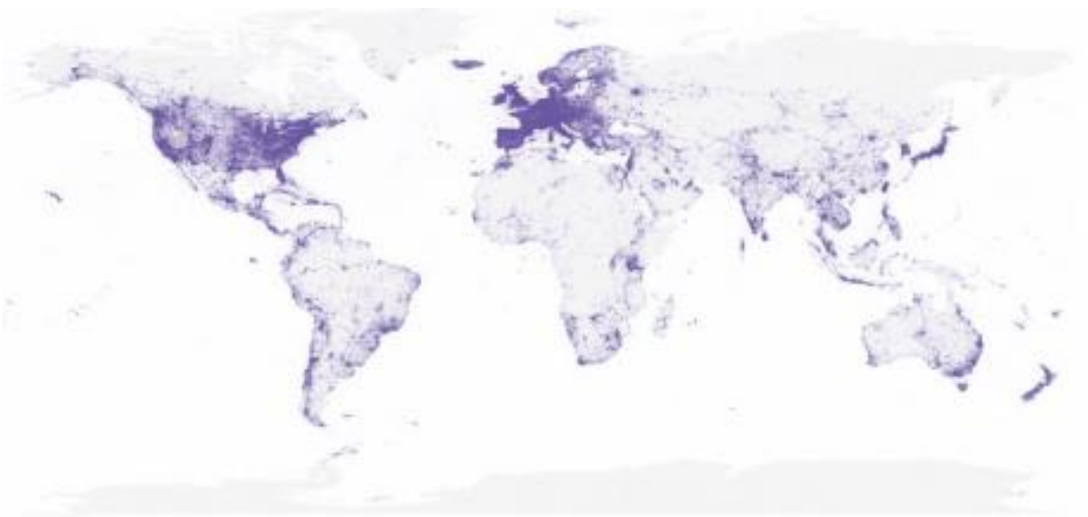

Figure 2.4 Location of approximately 200 million geotagged photographs uploaded to Flickr from 2005 to 2012 (S. A. Wood et al., 2013)

Visitation rate estimates based on social media were validated using field data and the proportional distribution of visitors was confirmed. This study's scientific contribution was not only methodological in determining that the geographic distribution of photographs from Flickr were highly correlated with empirical visitation rates of 836 sites around the world, but also practical in providing an accompanying software model for a regression analysis of visitation dependent on the presence of natural and built features. My role was collaborating on the design and implementation of the model, which presented many challenges.

Technical challenges made development of this model difficult. Flickr uses a representational state transfer (REST) architecture for API access but does not provide a machine readable OpenAPI specification. Therefore, it is not possible to use a generic API tool to interface with their service. Instead, this requires use of an API kit provided by a third party or manual construction and running of RESTful commands aided by their documentation. The Flickr API access is for non-commercial purposes only and has a speed limit slowing access. The terms of unlimited access through a commercial license are not publicly available. From 2005 to 2010 Flickr users uploaded more than 6 billion photographs with approximately 200 million having a geotag. Given the volume of photo metadata and the limits of the Flickr API in terms of both methods of searching and throttled access, the metadata from approximately 2,000 photographs could be obtained per minute. This rate was slowed by overhead for structuring searches and known bugs in the API responses. Despite these challenges, it was possible to gather all the data, but it took more than six months.

In the resulting InVEST recreation model, the presence of Flickr users based on their geotag is the response variable in a regression with dependence on environmental attributes. These environmental attributes were derived from OpenStreetMap global data, the Oakridge National Laboratory LandScan global ambient population dataset, and the United Nations Environmental Program World Database on Protected Areas. OpenStreetMap is published under the Creative Commons Attribution-ShareAlike license and could be freely redistributed with the model. LandScan is a licensed data product and required that derivative works such as outputs from the model could not reconstruct the original dataset. The World Database on Protected Areas prohibits all redistribution of data without permission and, after approximately six months of waiting for a reply, it was stated that the data could not be included in the model in any form.

The development of this model informed this thesis in several ways. The proof of concept for a server-based ecosystem service assessment tool demonstrated the practicality of implementing similar web based tools. The ability to incorporate restricted datasets into the model was especially useful for the Flickr dataset, which had an uncertain license and the LandScan dataset, which had a restricted license. While the model did not use OWS standards, it did integrate methods from multiple tools. The need to interface each of these tools manually highlighted how standards like OWS would be useful for increasing interoperability and reducing development time.

2.2 Web Service Standards

Use of web service standards is fundamental to ESWS. There are many different web service standards, but they all have in common an application programming interface (API) that defines the grammar and vocabulary for machine to machine communication. In the following subsections, details of APIs are discussed, and an emphasis is placed on the OGC web service standards.

2.2.1 Application programming interface

An application programming interface (API) is the grammar and vocabulary for machine to machine communication (Lomborg & Bechmann, 2014). It defines how and what can be requested. It allows users to interface with the components of a system and combine them in novel ways that can be augmented with additional programming. Ideally, documentation lists all the functions and details how to call them and what they do. The advantage of an API is that it does not require the examination and understanding of the underlying code that is run, thus reducing the need for expertise and saving on time. Furthermore, this allows for the protection of intellectual property rights by concealing proprietary methods. Transparency and openness are essential for confidence in the accuracy of software. While assuring the value of intellectual property rights is often achieved through secrecy and obfuscation, this stands in contrast to the confidence that can be conveyed through open-source code. At a minimum, software should include an API to maximize its utility. APIs that are created with formal specifications such as OpenAPI or RESTful API Modeling Language (Montcheuil, 2015) are especially useful because they can be used with generalized tools and software libraries.

2.2.2 Table Joining Service standard

The Table Joining Service (TJS) standard is for tabular data (P. Schut, 2010). Biophysical data in tabular form can be necessary and appropriate for analysis. The biophysical parameters of species must often be used because it is impractical to gather field data. In some cases, this is the result of lack of resources or an inaccessible site, and while field data would be desirable the qualities of well-studied species can mean that field data is not always necessary. In some cases, it is necessary to use even more generalized data such as biophysical parameters for a particular plot of land. While this lacks precision, it can still be useful. This need for tabular data means that a web service that supports indexing and sharing of tabular data is necessary. This is still spatial data as a geographic identifier contained within a TJS dataset may reference pixel identifiers in a raster or object identifiers in a georeferenced vector dataset.

Unfortunately, there has been poor uptake of the TJS standard. This is reflected in the lack of a maintained, fully functional implementation. The TJS third party plugin for GeoServer (https://github.com/thijsbrentjens/geoserver) is for a version of GeoServer that is no longer maintained and a standalone Python based TJS (https://github.com/neogeo-technologies/OneTjs) is no longer compatible with all the required libraries. The lack of a TJS implementation highlights the need for canonical implementations of OWS.

2.2.3 Web Coverage Service standard

The Web Coverage Service (WCS) standard is for raster data. Raster data is a regular, typically two-dimensional, grid of values (Baumann, 2012). These values can be ordinal, nominal, discrete, or continuous. Ordinal data is data that represents something such as wind direction. Nominal data is data that represents something like a land use class. Discrete data is data that represents something like number of visitors. Continuous data is data that represents something like temperature. Typically, the geospatial reference of a raster is contained within a sidecar file or embedded in file metadata. Because of the regular positioning of locations within a raster, the area can be defined by a few reference points, normally the corners of the grid, and a formula that describes the way in which to subdivide the area and the number of times to do so. In this way, the values within a raster and their geographic locations can be stored efficiently. At times, though, this means that with standalone files the metadata can more easily become lost or damaged and therefore render the data unusable. For efficiency's sake the WCS typically consists of a metadata file with an external reference to the image file with the raster values. This could bring about circumstances where the metadata references data that is no longer available.

2.2.4 Web Feature Service standard

The Web Feature Service (WFS) standard is for vector data (Vretanos, 2014). Vector data can more colloquially be referred to as "shapes". These shapes can be points, lines, or polygons and further extended into collections, as is the case with multipoints, and other geometries including surfaces.

Historically, the most common format to store geographic vector data is the ESRI shapefile (ESRI, 1998). The shapefile format is widely supported and very well documented. It consists of a minimum of three files, the .SHP, .SHX, and .DBF. for geometry, indexing, and attribute values, respectively. Typically, there is also a .PRJ file that contains the spatial projection information. This means that a shapefile consists of the .SHP and three sidecar files, which in the absence of any of those the shapefile can become unusable from the loss of information. Technically, only the .SHP is strictly necessary but in the absence of a .DBF no attributes of the shapes are known and in the absence of a .PRJ the way in which the internal coordinate system for shapes corresponds to Earth is unknown. All the information contained in a .SHX file can be derived from a .SHP file but all the most common GIS, including ArcGIS, QGIS, and GRASS will not read the data without it. The .SHX file contains the byte offset for each shape in the .SHP file and presumably was created because disk seek and read times used to be demanding on computers.

The legacy of shapefile readers means that when the .SHX file is missing there is an error. The complexity of shapefiles is understandable but often results in errors, especially in teaching environments. Most commonly, in its simplest form the WFS contains all the data and metadata for shapes combined. This means that all geometry, attributes, and spatial references are integrated in a single place and, therefore, easier to use and less prone to errors. The WFS does also support serving data in multiple formats, including shapefile.

2.2.5 Web Processing Service standard

The Web Processing Service (WPS) standard is used to exchange model identifiers, metadata on their parameters, and the desired values for those parameters for a model run (Mueller & Pross, 2015). Model parameters can be complex data, literal data, or bounding box data. Complex data is encoded data with a specified format. Literal data is a single value or a range of values with types such as integer, floating point, or string and an associated unit such as meters or degrees Celsius. Bounding box data is the minimum and maximum X and Y coordinates for a place and the associated coordinate reference system, also known as projection.

2.2.6 Other web service standards

There are several other OWS with varying levels of relevancy to ecosystem service assessment. The Web Map Service (WMS) is a standard for exchanging formatted geographic data in the form of processed and stylized maps in a georeferenced image format (de la Beaujardiere, 2006). The Catalogue Services (CS) is a standard to publish and search for data (Nebert et al., 2016). The Web Coverage Processing Service (WCPS) is a standard for processing raster images (Baumann, 2009). While these services could contribute to an ecosystem service assessment, they are not critical to performing an analysis. For this reason, they are not discussed further here.

2.3 Spatial Data Infrastructure

Spatial data infrastructure (SDI) is infrastructure for the management of spatial data, metadata, processes, and users. In SDI, resources are advertised and discoverable by users using a client. Depending on the features of the SDI and client everything from simple tasks like the downloading of data to sophisticated models can be run. Many SDIs, like GeoNetwork, GeoNode, and geOrchestra, primarily focus on the sharing and distribution of data and often augment GeoServer or other SDIs to achieve the desired features. Less frequently, there are SDIs like VLab (http://www.ecopotential-project.eu/products/vlab.html), Swiss Data Cube (https://www.swissdatacube.org/), and Google Earth Engine (https://earthengine.google.com/) that function as full analysis platforms.

2.4 SWATCH21

SWATCH21 presented a case study well suited for the creation of interoperable workflows (Lehmann et al., 2019). The objective of the SWATCH21 project was to improve "understanding of eco-hydrologic services at the catchment level, and biodiversity at the river scale" with the goal of answering the following research questions:

- "How can we improve the access to input data for hydrological and ecological modeling?
- What is the role of glacier and snow in modifying the hydrological services?
- How can we best assess hydrologic services supplies and demands with the available data and tools?
- What will be the impact of the main hydrologic changes on species diversity in rivers?

- Can we meet the targets of multi-sectorial river-related policies under different climate and land use forecasting scenarios?
- How detailed do ecosystem service data and models need to be to answer relevant policy questions?" (Lehmann et al., 2019, p. 182)

This calls for the use of many different data sets with diverse sources and a variety of analysis software including SWAT, InVEST, and species distribution modeling. The creation of the SWATCH21 tool API would establish the protocol for the integration of these components.

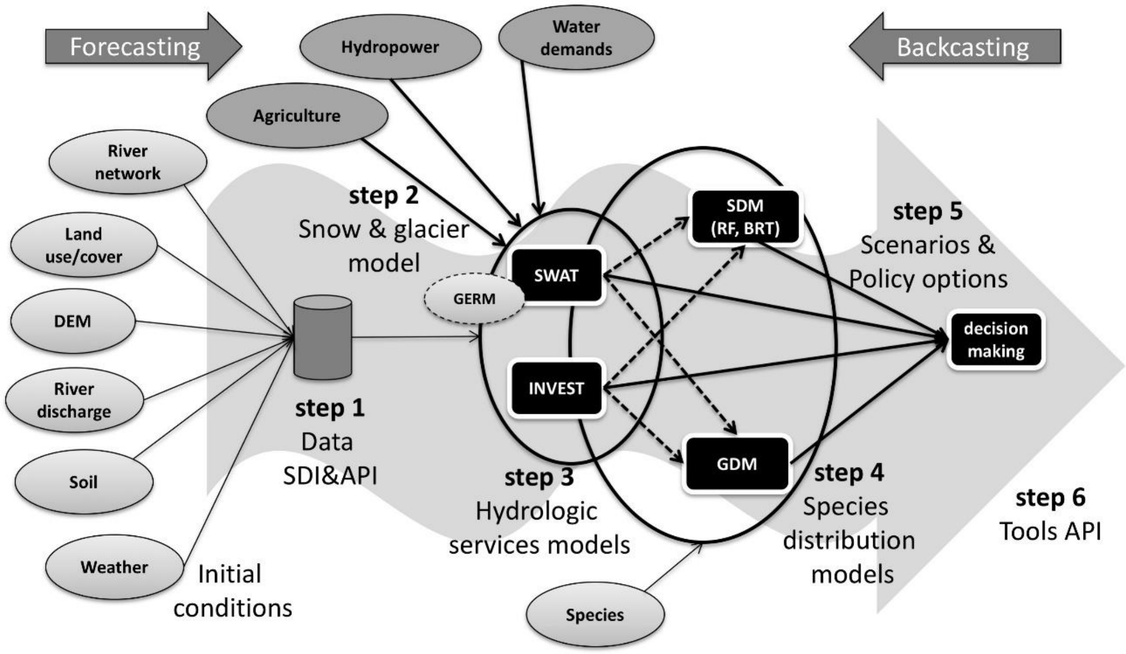

Figure 2.5 Architecture of the SWATCH21 project (Lehmann et al., 2019)

Still greater value can be achieved for SWATCH21 and ecosystem service assessments with the creation of a more general tool that enables the production of interoperable workflows to:

1. produce dynamic workflows for more robust results,
2. increase immediate value by improving access and facilitating reproducibility,
3. increase long term value by making the production of longitudinal studies easier,

4. and establishing a foundation that could more easily be expanded or built on for new research reducing demand on human and computer resources.

2.4.1 ECOSYSTEM SERVICE WEBSERVICE (ESWS)

The original contribution of this thesis is the incorporation of Open Geospatial Consortium Web Service (OWS) standards into ecosystem service assessment in the form of the Ecosystem Services Web Service (ESWS). This is a natural, but novel evolution that could offer considerable benefits for increasing the robustness of the science of ecosystem service assessment. Use of OWS for each step within an ecosystem service analysis could represent a more complete solution that, to my knowledge, has not been achieved by others to date. The OWS, and other technological advances, are being incorporated into the practice of GIScience through ad hoc approaches and various standards. This ad hoc approach tends to be piecemeal and incomplete.

Rather than intermittently electing certain data or analysis processes to use interoperability standards the ESWS has them at its core, linking all components in a cohesive way that is especially timely (Lehmann et al., 2017). The maturity of ecosystem service software (S. L. R. Wood et al., 2018) and the OWS standards (Giuliani, Lacroix, et al., 2017) mean that an integrated approach to the collection, processing, and analysis of spatial data for ecosystem service assessment is feasible. If the impact of differing ecosystem service assessment conclusions were limited to academic discourse alone, such a contribution would perhaps be less urgently needed. However, ecosystem service assessment science is now used to inform governance and management decisions on critical sustainability concerns the world over. Such analyses are widely used by international organizations, national governments, and conservation civil society organizations to facilitate decision making in many complex, dynamic contexts (Bateman et al., 2013; Díaz et al., 2018; Ouyang et al., 2016).

I addressed the problem of interoperability of ecosystem service assessment tools by developing the ESWS workflow platform using international standards for accessing methods and exchanging geographic data. Through experimentation, it was determined that OWS offers the most complete set of standards to achieve this. However, no comprehensive standards implementation exist that integrates software and tabular, raster, and vector data. Therefore, it was necessary to construct a hybrid solution. I did so using GeoServer, PyWPS, and custom-built code to utilize the full suite of OWS services necessary for ecosystem service assessment tools. The biggest challenge was linking inputs and outputs between WPS and tools. This requires detailed metadata about data requirements and understanding the decision tree determining outputs for a given tool. Because InVEST is a free and open-source tool examination of the source code readily provides the knowledge to know how each permutation of optional inputs leads to a fixed set of outputs. With other tools, the outputs cannot always be known at run time and, in such cases, this nondeterminism requires composite outputs acting as collections. Once these tools are encapsulated in interoperable middleware, they can be combined and added to the ESWS.

2.4.2 ESWS Architecture

Traditionally the collection, preprocessing, and analysis of spatial data for ecosystem service assessment is a time consuming and laborious process. With the use of OWS for ESWS there is great potential to streamline this. Collecting data usually involves using search engines to find web pages containing text that includes the search terms followed by one or more steps to access the desired data before preprocessing. With OWS, a search query yields direct links to data sources and a variety of preprocessing can be applied before downloading the data. The preprocessing can be simple, like subsetting, which is natively supported by OWS data standards, or more advanced, such as with a geographic buffer via WPS. Given enough metadata, OWS data sources can be matched up with data requirements for a WPS in an automated or semi-automated way, making the search for data even easier (Nativi & Bigagli, 2009).

The ESWS takes the approach of software as a service (SaaS) and encapsulates each step of ecosystem service assessment in OWS, including all inputs and outputs. This allows for any point of the workflow to be modified or redirected into a new process before continuing and differs from other approaches that only allow for the consumption of initial inputs and publishing of final outputs via open standards. Despite the increase in computational overhead this has the advantage of exposing all possible avenues for change and provides a mechanism to integrate unexpected innovation. Furthermore, since OWS are APIs they are platform agnostic and do not require specific software or hardware for implementation and can be used with many existing resources.

2.4.2.1 Template

The concept of SaaS is well established (Cusumano, 2010; Mouradian et al., 2018; Venters & Whitley, 2012). In the domain of geosciences, WPS can be used as an API for SaaS. Version 1.0 of WPS required static inputs but with the introduction of version 2.0 dynamic nested inputs are allowed. The generic process for creating a WPS from a model requires understanding the model specifications for inputs and outputs and implementing middleware to relay data into and out of a model. In the case of ecosystem service models, these inputs are primarily spatially explicit and TJS, WCS, and WFS connectors can be used for greater interoperability.

2.4.2.2 InVEST

The integration of InVEST into the ESWS is a proof of concept for the approach to enhancing ecosystem service assessment tools with OWS. Data in InVEST consists of literals such as integers, floats, and strings, and more complex types of tabular data, usually with geographic identifiers, raster data, and vector data (*reference*). The raster and vector data are read and written with the geographic data abstraction library (GDAL). These are typically in the geographic tag image file format (GeoTIFF) and Shapefile format, respectively, but can also be in a variety of other formats. The WCS and WFS, which are used for raster and vector data, respectively, can be directed to return data in GeoTIFF and Shapefile formats, making directly compatible inputs for InVEST. Tabular inputs to InVEST fit the TJS data model but require conversion from the Geographic Data Attribute Set (GDAS) format. It should be noted, however, that as there is no maintained TJS implementation the ESWS simulates TJS with the transfer of tabular data using the common comma separated values (CSV) table format that is used natively in InVEST. The API for InVEST is documented, making it easier to encapsulate in a WPS. Each InVEST model is run with a function called execute, to which all the model parameters are passed. With the help of the InVEST documentation and source code each of the inputs for the InVEST model can be identified, labeled, and data typed then associated with a WPS compatible format, making the construction of a WPS possible. In this way, WPS model parameters can be passed to an InVEST model and any TJS, WCS, and WFS sources can be received as InVEST compatible inputs. Therefore, InVEST can readily be made to read data from web services.

InVEST can also readily be made to write data to web services. While one could modify the source code of InVEST to output directly to TJS, WCS, and WFS hosts, the shortest path to the publishing of InVEST outputs to OWS is by converting the outputs from an unmodified version of InVEST. As described above, the conversion from OWS data sources to InVEST compatible formats is relatively simple but the conversion from InVEST formats to OWS is more complicated. This can be accomplished with the current state of available OWS libraries and supporting tools by making use of the GeoServer representational state transfer (REST) API. Using the API kit GSconfig (https://github.com/planetfederal/gsconfig), a series of simple Python commands can be used to upload Shapefiles and register GeoTIFFs into GeoServer. Tabular data file outputs are simply registered with the TJS emulation as described above, making them ready for transfer.

An InVEST model run consists of input data, analysis software, and output data. Above, I explained how input and output data could be consumed and published through OWS. The WPS standard is used to specify a list of inputs to provide to a process that will produce a list of outputs. This is readily compatible with linking InVEST models by specifying WPS outputs as inputs to an InVEST WPS. The complication, however, is the use of nested and optional inputs for InVEST models. For example, an optional input for the water yield model is the boolean whether to calculate the amount and value of hydropower that could be produced. If this input is set to true, then a nested input of a hydropower valuation table is required. Prior to WPS version 2.0, dynamic inputs such as these were not supported. This meant that every combination of nested inputs required its own separate process.

2.4.2.3 SWAT

The complexity of SWAT and its use of Microsoft Open Database Connectivity (ODBC) (Taylor et al., 2015) makes integration into a WPS challenging. The use of the Microsoft ODBC more readily calls for the Windows operating system. However, the use of OWS more readily calls for a Linux operating system. With the introduction of SWAT+, this discrepancy has been resolved by the replacement of the Microsoft ODBC with the open source and cross platform SQLite (https://www.sqlite.org/). This means that SWAT+ can more readily be deployed on Linux and, furthermore, benefits from a variety of other improvements. However, for the SWATCH21 project SWAT modeling of Switzerland was done without SWAT+ and, therefore, requires the Windows operating system. For the ESWS the integration of SWAT required the creation of a Windows virtual machine that, due to the license of the Windows operating system, cannot be shared. This inability to share goes against the ethos of the ESWS but was necessary for the SWATCH21 project. In the future it is hoped that SWAT+ will be integrated into the ESWS.

2.4.3 ESWS OWS Implementation

The ESWS is an end-to-end solution using OWS. This requires both client and server components for each web service. The client components make use of formatted URLs and OWSlib. The server components make use of GeoServer and PyWPS. This combination was arrived at after an exhaustive examination of possibilities. Through the generous work of hundreds of open-source community members these tools were created and made available to all. The implementation of a white paper under the best of circumstances can be challenging. Predictably, with a community-based project and hundreds of members there can be some inconsistencies. The separate implementation of OWS client and server components and different interpretations of corresponding white papers meant that, in some cases, optional parameters were erroneously implemented as mandatory parameters and simple variations such as capitalization differences sometimes led to incompatibilities. The challenge in isolating these sources of error can be substantial. In the time since ESWS development first began, many issues have been fixed and contributions to the code through merge requests completed in PyWPS (185 issues and 254 merges), OWSlib (133 issues and 248 merges), and GeoServer (1,286 issues and 3,290 merges).

Three libraries important for the ESWS are:

- PyWPS (https://github.com/geopython/pywps),
- OWSlib (https://github.com/geopython/OWSLib), and
- GSConfig (https://github.com/boundlessgeo/gsconfig).

PyWPS is used as the WPS server. This was desirable because it is written in Python, relatively simple to use. Furthermore, the support for WPS in GeoServer is incompatible with InVEST. Specifically, the Python interpreter in GeoServer uses Jython and does not natively have all the libraries required for InVEST. Therefore, server components for WPS were implemented externally to GeoServer using PyWPS. OWSlib is used in some of the processing of WFS and WCS transactions. GSConfig is used to register external raster data and upload internal vector data to GeoServer.

2.4.3.1 TJS implementation

Tabular data is stored locally as a file and advertised through a basic HTTP file server. This is not compliant with the OWS table joining service (TJS) standard. Unfortunately, there is no maintained TJS standard. Instead, the HTTP file server simply lists the tabular data files registered in a simple webpage. The client side of the TJS is done by parsing the webpage for the URLs of the data files.

2.4.3.2 WCS implementation

Raster data is advertised through the native web coverage service (WCS) for GeoServer. The rasters are stored externally and registered using GSConfig. Raster data is downloaded with a GET http request using a formatted URL.

2.4.3.3 WFS implementation

Vector data is advertised through the native web feature service (WFS) for GeoServer. The vectors are stored internally and uploaded using GSConfig. Vector data is downloaded with a GET http request using a formatted URL.

2.4.3.4 Parameters

PyWPS is used to host the web processing service (WPS) middleware and relay inputs and outputs between web services and the desktop software. This requires a precise understanding of all the inputs and outputs for a model and the creation of a PyWPS process class instance for each model. There were some attempts to automate this process but there was insufficient metadata to do so. In the case of InVEST, the parameter file driven graphical user interface provides metadata on model inputs but no metadata on model outputs. A feature request for embedded model output metadata has been made but it is not a priority for the Natural Capital Project.

2.4.4 ESWS Implementation

Given the potential benefits of ESWS and the desire to improve ecosystem service assessments, I have made it freely available under the MIT license (https://esws.unige.ch). The prototype uses the Python libraries Django, OWSlib, GSconfig, PyWPS, and InVEST, along with several standard libraries. This solution uses a custom-built Python based Django web application user interface. The application retrieves tabular data from a simple HTTP file server as a pseudo-TJS. It retrieves and stores spatial data on GeoServer with WCS and WFS via GSconfig. Ecosystem service software is executed via custom processes in a PyWPS server with a WPS.

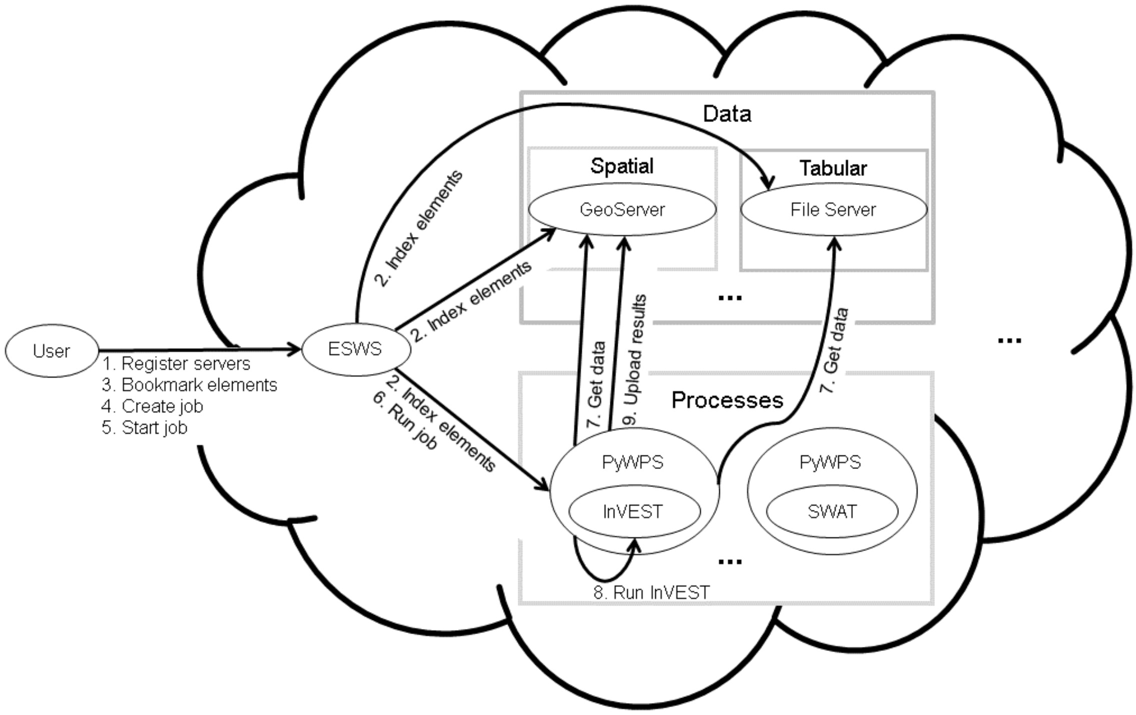

Figure 2.6 ESWS prototype architecture showing direction and type of requests for an InVEST model run (Lacayo et al., 2021)

The prototype consists of four components (Figure 2.6):

- Frontend client,
- Tabular data server,
- Spatial data server, and
- Processing server.

Each of these is independent and can be hosted on separate computers. Where possible, communication between these elements is done via OWS with representational state transfer (REST) commands and formatted URLs, which allows integration of new OWS compliant third-party components. The frontend client is a dashboard where servers are added, and their resources are automatically indexed (Figure 2.7). For example, registering a WPS server will give a complete list of the WPS processes available which can then be bookmarked individually for quick use. A processing job can be created with those WPS processes, yielding a form where each tabular or spatial data parameter can be set using drop down boxes populated with the available OWS data (Figure 2.8).

Local WCS

URL	http://127.0.0.1:8080/gs215/ows
Registrations	5
Jobs	0

Bookmarked Elements

Action	Id
Unbookmark	swatch21:ch_depth
Unbookmark	swatch21:ch_eto
Unbookmark	swatch21:ch_lulc
Unbookmark	swatch21:ch_pawc
Unbookmark	swatch21:ch_precip

Total: 5

Unbookmarked Elements

Action	Id
Bookmark	invest:depth_to_root_rest_layer
Bookmark	invest:eto

Figure 2.7 Screenshot of ESWS prototype WCS server details as specified by OWS results showing layers bookmarked for active use (Lacayo et al., 2021)

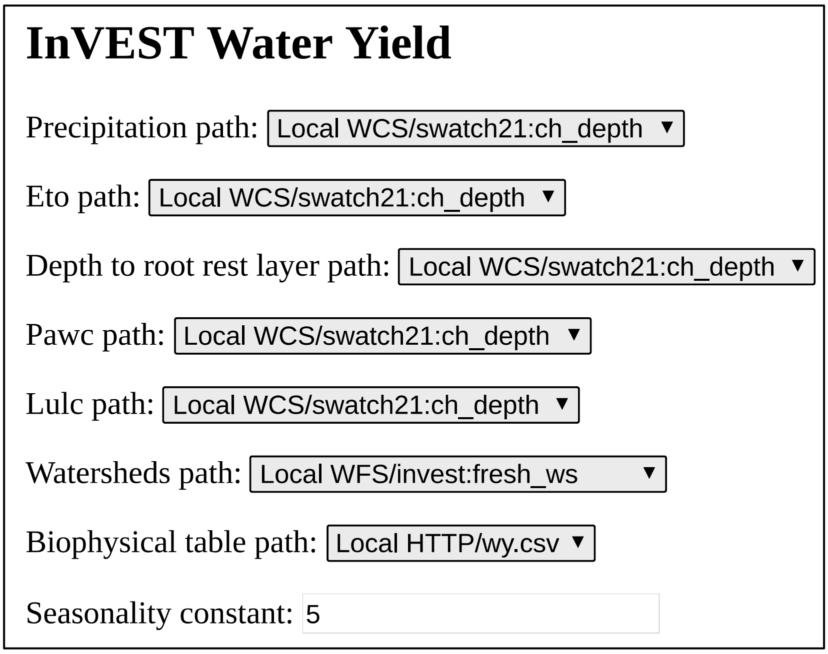

Figure 2.8 Screenshot of ESWS prototype WPS server job creation for InVEST Annual Water Yield showing automatic form generation as specified by OWS results with fields populated by bookmarked layers of the corresponding data types (Lacayo et al., 2021)

This separation between the user, data storage, and processing adds complexity but promotes data provenance. Since all changes are done remotely, the workflow is self-documenting and allows both the original analyst and any others granted access to examine and run it to produce results. Workflows can be iterated on by making small changes to each job such as applying a range of values to a parameter. This can be especially useful for sensitivity, specificity, and exploratory analyses. Results are stored remotely, making sharing a simple matter of user permissions. This combination of capabilities can facilitate collaboration by streamlining the sharing of data, processes, and results. This transition from data to results is preserved in a workflow that can be edited to incorporate updates to data or changes in the direction of analysis. Because the ESWS requires the availability of a resource within a network to function, evaluating the ESWS using the Nüst et al. (2018) criteria for reproducible research (Section 2.5) reveals that all criteria are satisfied at the highest or second highest level, depending on user preferences.

2.4.5 ESWS Demonstration

Switzerland is a data-rich country, but it can be difficult to gather the data. The provision of hydrologic services in Switzerland and impacts of expected environmental changes has not been studied at the national level (Lehmann et al., 2019). As a demonstration of the capabilities of the ESWS, the average annual water yield is calculated with InVEST at the subbasin level to understand spatial variability. Understanding this spatial variability is important because it shows differences in water supplies to rivers and lakes that are essential for aquatic life. This is a good case study for the ESWS because it uses user specified constants, tabular data, and spatial data in multiple formats that are stored on different servers. Furthermore, as data sources and methods change over time the corresponding ESWS workflows can be easily updated.

The InVEST water yield model is a water balance model that calculates average annual yield as the remainder from precipitation after transpiration, evaporation, and ground water recharge are allocated. The model requires raster data for root restricting layer depth, precipitation, plant available water content, average annual reference evapotranspiration, land use and land cover, and vector data for watersheds. These come from global coverage sources of the Harmonized World Soil Database (https://www.fao.org; FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), WorldClim (http://www.worldclim.org/; Fick & Hijmans, 2017), ISRIC Soil Information System (https://www.isric.org), Global Aridity and PET Database (https://cgiar-csi.org; Zomer et al., 2007), GlobCover (https://due.esrin.esa.int; Arino et al., 2012), and level 7 and 12 HydroBASINS from HydroSHEDS (https://hydrosheds.org; Lehner & Grill, 2013), respectively. Additionally, a constant for precipitation seasonality and a biophysical table that contains the root depth and plant evapotranspiration coefficient for each land use land cover type are required.

After finding or creating OWS resources with these data sources the ESWS can be used to bring data and methods together to calculate average annual water yield with the InVEST water yield model. The steps consist of registering the OWS data servers and bookmarking the needed data sets (Figure 2.7), generating and running an InVEST water yield WPS job with the appropriate parameters (Figure 2.8), and manually visualizing the results (Figure 2.9).

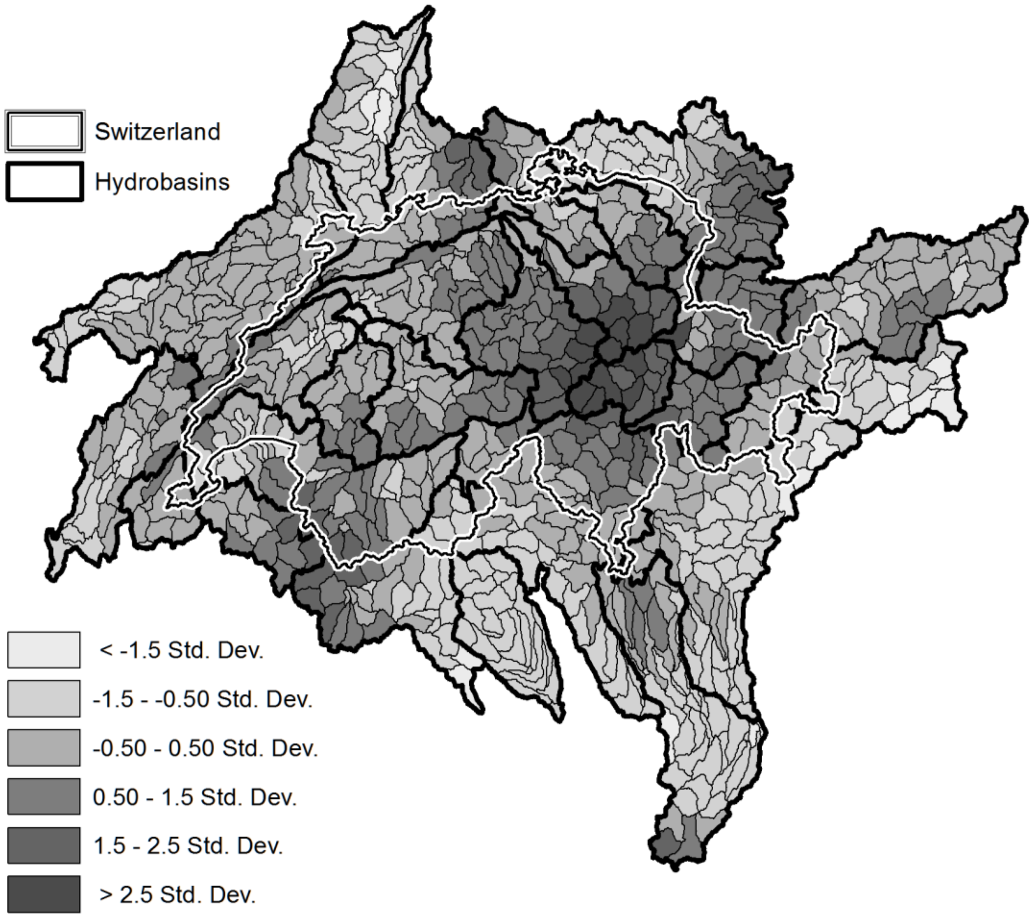

Figure 2.9 Water Yield per level 7 and 12 HydroBASIN in Switzerland (Lacayo et al., 2021)

2.4.6 SWATCH21 Integration Into ESWS

The results from section 4.4 demonstrate improvements in bringing ecosystem service into practice through interoperable workflows and has important implications for SWATCH21. The hydrological and species distribution models for SWATCH21 continue to be developed, but on completion they can be integrated into the ESWS and:

1. Enable the production of more robust results,
2. Raise the scientific credibility with ready reproduction,

3. Increase longevity with easy updates for new climate and land use scenarios,
4. Facilitate future studies that expand on the research,

making an important contribution to the larger field of ecosystem service assessment.

2.5 Contributing Projects and Research Papers

2.5.1 Projects

This research benefited from two international projects funded by the European Commission and one national project funded by the Swiss National Science Foundation.

EcoPotential (http://www.ecopotential-project.eu/) was a project funded by the Horizon 2020 European Commission (https://cordis.europa.eu/project/id/641762) that started on June 1, 2015 and ended on October 31, 2019. It created a unified framework for ecosystem studies and management of protected areas to improve future ecosystem benefits for humankind. The ECOPOTENTIAL Virtual Laboratory Platform (VLab) was one of the primary outputs of the project and showcased the value of a cloud-based solution that allowed modelers to port their model to the platform. VLab emphasized interoperability through data brokering and containerization of software. In part, this was the inspiration for the work in this thesis. The distinction between VLab and ESWS is that, while VLab is a platform to which models must be ported, ESWS is a proof-of-concept workflow tool for linking existing data and software resources in a decentralized way to maximize interoperability of existing resources through web services.

ERA-PLANET (http://www.era-planet.eu/) is a project funded by the Horizon 2020 European Commission (https://cordis.europa.eu/project/id/689443) that started on February 1, 2016 and will end January 31, 2022. ERA-PLANET supports the implementation of European environmental policy by improving the monitoring of the global environmental and sharing of Earth Observation information and knowledge. The development and enhancement of VLab was also supported by ERA-PLANET and as under ECOPOTENTIAL this benefits ESWS as above.

SWATCH21 (https://www.unige.ch/envirospace/projects/swatch21/) was a project funded by the Swiss National Science Foundation (http://p3.snf.ch/project-173206) that started on July 1, 2017 and ended on June 30, 2020. It linked eco-hydrologic processes and services to aquatic biodiversity at river and catchment levels under climate and land use scenarios. While direct funding has ended, this project persists and continues to be the catalyst for the ESWS.

2.5.2 Contributing Research Papers

The thesis has its foundation in the seven coauthored publications listed below with their abstracts and a brief description of their contributions to the work.

In “A framework for ecosystem service assessment using GIS interoperability standards” (Lacayo et al., 2021), the ESWS is introduced and the core work of developing it is discussed.
Abstract: Ecosystem Services Web Services (ESWS) are new web-based approaches to quantifying the benefits that humans derive from nature. Specifically, ESWS are the application of open web standards to ecosystem service assessment to facilitate creation, iteration, and dissemination in a seamless way. This integration streamlines collaboration, automation, and curation, while providing an open interface through which novel advances can be incorporated. The approach creates a new level of interoperability through data provenance whereby each transition between processing steps employs standards that ensure cohesive workflows across models and platforms. This imparts a modularity that can be examined and extended at every step.

In “SWATCH21: A project for linking eco-hydrologic processes and services to aquatic biodiversity at river and catchment levels” (Lehmann et al., 2019), the SWATCH21 project is discussed, as well as the SWATCH21 Tool API that inspired the ESWS.
Abstract: The objective of the SWATCH21 project is to improve our understanding of eco-hydrologic services at the catchment level, and biodiversity at the river scale. Six research questions are proposed: (i) How can we improve the access to input data for hydrological and ecological modeling? (ii) What is the role of glacier and snow in modifying the hydrological services? (iii) How can we best assess hydrologic services

supplies and demands with the available data and tools? (iv) What will be the impact of the main hydrologic changes on species diversity in rivers? (v) Can we meet the targets of multi-sectorial river-related policies under different climate and landuse forecasting scenarios? (vi) How detailed do ES data and models need to be to answer relevant policy questions? The above questions are tackled through an integrated framework to access, share, process, model, and deliberate on hydrologic ecosystems services. State-of-the-art models have been selected, and will be compared and improved to model different ecosystems and their services. Initial results from a first SWAT model of Switzerland and Species Distribution Models are presented. Expected outputs from various climate and land use change scenarios include rivers' hydrology, predicted biodiversity, and the assessment of ecosystem services in terms of provisioning services (e.g. water resources), regulating services (e.g. nutrient, sediment and flood water retention), and cultural services (e.g. biodiversity, recreation). The expected outcome of the project is to improve integrated evidence-based water policy in the future through the analysis of tradeoffs and synergies between services.

In "Impacts of Land-Use and Land-Cover Changes on Water Yield: A Case Study in Jing-Jin-Ji, China" (Li et al., 2018) a manual ecosystem service assessment is discussed. Lessons learned from serving as a technical adviser to the study informed the development of the ESWS.

Abstract: Knowing the impact of land-use and land-cover (LULC) changes on the distribution of water yield (WY) is essential for water resource management. Using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, we investigated the spatial-temporal variations of WY from 1990 to 2015 in China's northern semi-arid region of Beijing–Tianjin–Hebei (Jing-Jin-Ji). We quantified the combined effects of LULC dynamics and climatic variation on WY. Furthermore, we identified the relative contribution of main LULC types to WY. For our study region, the built-up area increased by 35.66% (5380 km2) during the study period. In the meantime, cropland, grassland, and wetland decreased continuously. The expansion of built-up area and decline of vegetated land led to an increase of 1047 million m3 (5.1%) in total WY. The impacts of LULC changes on WY were mainly determined by the biophysical characteristics of LULC composition. Vegetated land has relatively lower

WY coefficients due to higher rates of evapotranspiration and water infiltration. Built-up areas and bare land have higher WY coefficients as a result of their impermeable surface. The spatial-temporal analysis of WY with specification of WY coefficients by LULC types can facilitate integrated land-use planning and water resource management.

In "Lifting the Information Barriers to Address Sustainability Challenges with Data from Physical Geography and Earth Observation" (Lehmann et al., 2017), the research problems and initial theoretical framework that call for and inform an ESWS-like solution are discussed.
Abstract: Sustainability challenges demand solutions, and the pace of technological and scientific advances in physical geography and Earth observation have great potential to provide the information needed to address these challenges. This paper highlights five online tools and initiatives that are lifting barriers to address these challenges. The enviroGRIDS project in the Black Sea catchment demonstrates how the use of spatial data infrastructures can facilitate data sharing. Google Earth Engine is providing solutions to challenges of processing big data into usable information. Additionally, application programming interfaces allow outsiders to elaborate and iterate on programs to explore novel uses of data and models, as seen in the Berkeley Ecoinformatics Engine. Finally, collaborative mapping tools, such as Seasketch/MarineMap and the InVEST software suite, allow engagement within and between groups of experts and stakeholders for the development, deployment, and long-term impact of a project. Merging these different experiences can set a new standard for online information tools supporting sustainable development from evidence brought by physical geography combined with socioeconomic conditions.

In "Blue water scarcity in the Black Sea catchment: Identifying key actors in the water-ecosystem-energy-food nexus" (Fasel et al., 2016), the complexities of water scarcity were analyzed and discussed, highlighting the importance of tradeoff analysis.
Abstract: Large-scale water scarcity indicators have been widely used to map and inform decision makers and the public about the use of river flows, a vital and limited renewable resource. However, spatiotemporal interrelations among users and administrative entities are still lacking in most large-scale studies. Water scarcity and

interrelations are at the core of the water-ecosystem-energy-food nexus. In this paper, we balance water availability in the Black Sea catchment with requirements and consumptive use of key water users, i.e., municipalities, power plants, manufacturing, irrigation and livestock breeding, accounting for evaporation from major reservoirs as well as environmental flow requirements. We use graph theory to highlight interrelations between users and countries along the hydrological network. The results show that water scarcity occurs mainly in the summer due to higher demand for irrigation and reservoir evaporation in conjunction with relatively lower water resources, and in the fall-winter period due to lower water resources and the relatively high demand for preserving ecosystems and from sectors other than irrigation. Cooling power plants and the demands of urban areas cause scarcity in many isolated locations in the winter and, to a far greater spatial extent, in the summer with the demands for irrigation. Interrelations in water scarcity-prone areas are mainly between relatively small, intra-national rivers, for which the underlying national and regional governments act as key players in mitigating water scarcity within the catchment. However, many interrelations exist for larger rivers, highlighting the need for international cooperation that could be achieved through a water-ecosystem-energy-food nexus.

In “Using social media to quantify nature-based tourism and recreation” (S. A. Wood et al., 2013), published prior to the start of my PhD studies, the initial ideas that led to the ESWS were formed, and extensive lessons learned from serving as the primary software developer significantly shaped the development of the ESWS.

Abstract: Scientists have traditionally studied recreation in nature by conducting surveys at entrances to major attractions such as national parks. This method is expensive and provides limited spatial and temporal coverage. A new source of information is available from online social media websites such as flickr. Here, we test whether this source of ‘‘big data’’ can be used to approximate visitation rates. We use the locations of photographs in flickr to estimate visitation rates at 836 recreational sites around the world, and use information from the profiles of the photographers to derive travelers’ origins. We compare these estimates to empirical data at each site and conclude that the crowd-sourced information can indeed serve as a reliable proxy for empirical visitation rates. This new approach offers opportunities to understand which elements of nature attract people to locations around the globe, and whether changes in ecosystems will alter visitation rates.

In “Coastal habitats shield people and property from sea-level rise and storms” (Arkema et al., 2013), published prior to the start of my PhD studies, the importance of ecosystem service assessment is discussed. Lessons learned from serving as a GIS analyst for this study informed the development of the ESWS.

Abstract: Extreme weather, sea-level rise and degraded coastal ecosystems are placing people and property at greater risk of damage from coastal hazards1–5. The likelihood and magnitude of losses may be reduced by intact reefs and coastal vegetation1, especially when those habitats fringe vulnerable communities and infrastructure. Using five sea-level-rise scenarios, we calculate a hazard index for every 1 km2 of the United States coastline. We use this index to identify the most vulnerable people and property as indicated by being in the upper quartile of hazard for the nation’s coastline. The number of people, poor families, elderly and total value of residential property that are most exposed to hazards can be reduced by half if existing coastal habitats remain fully intact. Coastal habitats defend the greatest number of people and total property value in Florida, New York and California. Our analyses deliver the first national map of risk reduction owing to natural habitats and indicates where conservation and restoration of reefs and vegetation have the greatest potential to protect coastal communities.

3. A FRAMEWORK FOR ECOSYSTEM SERVICE ASSESSMENT USING GIS INTEROPERABILITY STANDARDS

This paper was published online 12 May 2021 in *Computers and Geosciences*.

A framework for ecosystem service assessment using GIS interoperability standards[1]

Martin Lacayo [a,e], Denisa Rodila[a,b], Gregory Giuliani[a,b], Anthony Lehmann[a,c]

[a] enviroSPACE, Institute for Environmental Sciences, University of Geneva, 66 Bd. Carl-Vogt, CH-1205, Geneva, Switzerland

[b] GRID-Geneva, Institute for Environmental Sciences, University of Geneva, 66 Bd. Carl-Vogt, CH-1205, Geneva, Switzerland

[c] Dpt. F.-A. Forel for Environment and Water Sciences, Faculty of Sciences, University of Geneva, 66 Bd. Carl-Vogt, CH-1205, Geneva, Switzerland

[e] Corresponding author email: Martin.Lacayo@unige.ch

Code Availability

The code and documentation are available at: https://esws.unige.ch/

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[1] Martin Lacayo collaborated on all aspects of the conception of the research; designed and carried out the investigation; created, tested, and released the software; gathered and processed the demonstration data; wrote the manuscript and created the diagrams.

Denisa Rodila contributed to the research design regarding network efficiency and reviewed and edited the text and diagrams.

Gregory Giuliani contributed to the research design regarding spatial data infrastructure, reviewed and edited the text and diagrams, and co-supervised the investigation.

Anthony Lehmann contributed to the research design regarding hydrologic software including InVEST and SWAT, reviewed and edited the text and diagrams, co-supervised the investigation, and applied for and obtained funding that in part supported the project.

Highlights

- Ecosystem services (ES) are essential for human well-being.
- The reproducibility crisis in GIScience has implications for ES.
- Software interoperability can improve data provenance.
- Web services are used to create interoperable workflows.

Abstract

Ecosystem Services Web Services (ESWS) are new web-based approaches to quantifying the benefits that humans derive from nature. Specifically, ESWS are the application of open web standards to ecosystem service assessment to facilitate creation, iteration, and dissemination in a seamless way. This integration streamlines collaboration, automation, and curation, while providing an open interface through which novel advances can be incorporated. The approach creates a new level of interoperability through data provenance whereby each transition between processing steps employs standards that ensure cohesive workflows across models and platforms. This imparts a modularity that can be examined and extended at every step.

Keywords

Ecosystem Services; Web Services; Interoperability; Data Provenance; Reproducibility

3.1 Introduction

Ecosystem functions such as the retention of water, soil, and nutrients give rise to ecosystem services (ES) including water supply, erosion control, and nutrient cycling that are critical for human well-being (Costanza et al., 1997; Daily et al., 2009; Ehrlich & Mooney, 1983). This concept has been adopted widely as a means of explicitly linking changes in the environment and benefits to humans in spatial planning, biodiversity conservation, and in the broader realm of sustainability science. The ES framework supports contextualization and comparison of gains and losses that could result from action and inaction on different environmental policies and practices. Such analyses are increasingly demanded as global consumption increases and human populations grow, even as environmental degradation and climate change cause mounting uncertainty about capacity to meet these demands equitably and sustainably. At the same time there are some concerns about the robustness of ES data and analysis methods. Among these concerns is reproducibility. The “reproducibility crisis” in science, in general, and in geographic information science (GIScience), in particular (Nust et al. 2018) has been acknowledged. Reproducibility is a complex problem involving legal barriers (Borgman 2012), technical barriers, business models (Doctorow 2019), and academic reward mechanisms (Nüst et al. 2018). Here, we focus on aspects of reproducibility that are amenable to improvement through interoperability, with an emphasis on data provenance. Data provenance is of particular interest because the scale and scope of analyses and shifts to dry labs can mean there is no first-hand knowledge of the study area.

The Open Geospatial Consortium (OGC) Web Services (OWS) represent a major milestone for spatial data interoperability because they define a set of standards for exchanging geographic data that preserve ontological representation (Baumann, 2012; Mueller & Pross, 2015; P. Schut, 2010; Vretanos, 2014). They go far beyond the transfer of static data to include real time access to sensor networks, metasearch of data aggregators, and even data management for computation between models on a single computer or distributed across a network (Giuliani et al., 2012). This means that spatial data are not stored, queried, and retrieved without understanding of their inherent qualities, as is typically the case with the File Transfer Protocol (FTP). Instead, spatial primitives equivalent to equality, subtraction, and division, among others, can be used to remotely interact with the data before transferring with OWS. The significance of this is not only the unified communication protocols by which people can interact with data, but also the mechanism for machine-to-machine communication. In effect, OWS are analogous to a universal language for spatial data.

The central premise of this paper is that incorporating OWS into ES assessment in the form of Ecosystem Services Web Services (ESWS) is a natural, but novel evolution that could offer considerable benefits for increasing the robustness of ES assessment science and its policy applications. Use of OWS for each step within an ES analysis could represent a more complete solution that, to our knowledge, has not been achieved by others to date. The OWS, and other technological advances, are being incorporated into the practice of GIScience through ad hoc approaches and various standards, but there are specific ways in which ESWS is especially timely to lift barriers between data and decision making (Lehmann et al., 2017). The maturity of ES software and the OWS standards mean that an integrated approach to the collection, processing, and analysis of spatial data for ES assessment is feasible. If the impact of differing ES assessment conclusions were limited to academic discourse alone, such a contribution would perhaps be less urgently needed. However, ES assessment science is now used to inform governance and management decisions on critical sustainability concerns the world over. Such analyses are widely used by international organizations, national governments, and conservation civil society organizations to facilitate decision making in many complex, dynamic contexts (Bateman et al., 2013; Díaz et al., 2018; Ouyang et al., 2016).

In the remainder of this paper, we review the status of ES assessment methods and software. We then present an ESWS architecture and prototype illustrated by a demonstration of its application in Switzerland and discuss the value of this approach, including modularity and provenance logging. We conclude by assessing the promise of ESWS for strengthening science and improving the progression from data to informed decision making.

3.2 Background

3.2.1 Ecosystem service assessment software

There is momentous progress in both the science and software of ES. The science has progressed in concert with international initiatives such as the Millennium Ecosystem Assessment (http://www.millenniumassessment.org), the Economics of Ecosystems and Biodiversity (http://www.teebweb.org/), the Common International Classification of Ecosystem Services (https://cices.eu/), and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (https://www.ipbes.net/). The evolution of theory in this field is also reflected in developments such as greater precision in taxonomic systems used to describe and measure ES (Haines-Young & Potschin, 2018). The practice of ES assessment has also advanced with the development and extensive testing of specialized software (Ferrier et al., 2016), as well as adoption of software initially developed for other purposes such as the Soil and Water Assessment Tool (SWAT; Francesconi et al. 2016).

In 2018, Wood et al. identified twelve ES tools, comparing them based on ease of use and modeling capabilities across the ES categories of provisioning, regulating, supporting, and cultural services. The Artificial Intelligence for Ecosystem Services (ARIES; Villa et al. 2014) and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST; Nelson et al. 2009) stand out as covering the most ES, with InVEST considered the easier of the two to use. InVEST has the additional advantage of being free and open source and, therefore in addition to being available for use by all, anyone can also examine and modify its functionality. Created by the Natural Capital Project (https://naturalcapitalproject.org), InVEST formalizes a systematic approach to ES assessment. It consists of more than twenty ES models and supporting software tailored for specific applications, including the Resource Investment Optimization System (RIOS; Vogl et al. 2017) for watershed management and the Offset Portfolio Analyzer and Locator (OPAL; Mandle et al. 2016) for impacts of restoration.

ES assessment is often done manually without the use of ES specific software, but there are advantages in using ES software. Primary advantages are ease of use and defensibility due to standardization and reproducibility of results. InVEST is able to deliver these with low data requirements and high transparency. It facilitates the comparison of scenarios based on magnitude of results rather than precision. Such an approach supports timely and effective allocation of computing and human resources. Results can be used to quickly evaluate scenarios and highlight when and where more in-depth analysis could be valuable. For these reasons InVEST is particularly suitable for the ESWS demonstration case presented below.

3.2.2 "Reproducibility crisis" in GIScience

The "reproducibility crisis" is an emerging concern in GIScience. As in other disciplines, it brings into question the veracity of results and validity of any policy they inform. While historically uncertainty analysis has been considered due diligence and a sufficient concession to contrary opinions, in a post-truth era reproducibility is a critical defense against deniers. To this end, it is important to understand the various aspects of reproducibility, develop a means to categorize them, and identify possible solutions.

Nüst et al. (2018) created a reproducibility classification system for geospatial analyses, which they used to evaluate submissions to the Association of Geographic Information Laboratories in Europe (AGILE) conference series nominated for best full or short papers in the periods 2010 and 2012 to 2017. The classification system singles out 5 areas of reproducibility: input data, preprocessing, methods/analysis/processing, computational environment, and results, which were each evaluated as unavailable, documented, available, or available with an open license and permanent URL. The analysis of papers included a survey of authors, which found that a majority of respondents at least partially agreed with the evaluation of their papers as having low reproducibility while also indicating they thought reproducibility was important. Among the barriers mentioned, "several respondents noted a lack of supporting tools as a main impediment for reproducibility" (Nüst et al. 2018: p.14), as well as lack of time.

Interoperability offers at least a partial solution. Lack of time and lack of software are closely related and an abundance of one may compensate for the other. Improvements in software could produce easily shared workflows that would increase the ratio of reward to effort by reducing the time and expertise needed to examine a study in detail and reproduce it.

3.2.3 Open Geospatial Consortium Web Services

In this work we focus on four OWS standards and their value for ESWS: the Table Joining Services (TJS; Schut 2010) for tabular data, the Web Coverage Service (WCS; Baumann 2012) for raster data, the Web Feature Service (WFS; Vretanos 2014) for vector data, and the Web Processing Service (WPS; Mueller and Pross 2015) for computation. These standards do not have accompanying OGC implementations in software but are application programming interfaces (APIs), functionally a vocabulary and grammar for the transfer and processing of spatial data.

These standards specify the use of the Hypertext Transfer Protocol (HTTP) to communicate metadata and data inside of Extensible Markup Language (XML) documents. The metadata includes basic data like extent, projection, and provenance essential for data quality (Zhang et al., 2020), and the availability of basic query functions with parameters like counts and the list of names and types for datasets or processing functions. The data can be embedded directly in the XML response document but is more typically given by reference to an external data source that can be in a variety of formats. Although HTTP and XML may be unfamiliar to many, they are fundamental technologies for the Internet and very mature with extensive software libraries and documentation.

The use of OWS in the environmental sciences is arguably well established as exemplified in the Global Earth Observation System of Systems (GEOSS; https://www.earthobservations.org/geoss.php), Infrastructure for Spatial Information in the European Community (INSPIRE; https://inspire.ec.europa.eu/), and the Global Framework for Climate Services (GFCS; https://gfcs.wmo.int/) among other initiatives (Giuliani, Nativi, et al., 2017). However, these emphasize data services and are mostly used to discover or publish data at the beginning or end of analysis, with the intermediate steps of the analysis workflow typically done without OWS. This represents a break in what could otherwise be a cohesive interoperable workflow and inherently silos data, methods, and related knowledge. The ability to link processes throughout a workflow across models and platforms can be achieved with the creation of corresponding WPS (Castronova et al., 2013).This is a nontrivial task, as reflected by a low adoption rate. This is likely because the solutions for OWS are fragmented in the absence of an OGC implementation and more comprehensive supporting software as well as concerns about computational efficiency. Furthermore, while using OWS can lead to better documentation of the process leading to results with clearer data provenance, this is often not prioritized. While individually each OWS provides some advantages over other solutions, when used in concert there is potential for still greater advantages to be achieved. The challenge for ESWS is therefore to determine how to integrate TJS, WCS, WFS, and WPS into the core of ES analysis.

3.3 Architecture

Traditionally the collection, preprocessing, and analysis of spatial data for ES assessment is a time consuming and laborious process. With the use of OWS for ESWS there is great potential to streamline this. Collecting data usually involves using search engines to find web pages containing text that includes the search terms followed by one or more steps to access the desired data before preprocessing. With OWS, a search query yields direct links to data sources and a variety of preprocessing can be applied before downloading the data. The preprocessing can be simple, like subsetting, which is natively supported by OWS data standards, or more advanced, such as with a geographic buffer via WPS. Given enough metadata, OWS data sources can be matched up with data requirements for a WPS in an automated or semi-automated way, making the search for data even easier (Nativi and Bigagli 2009).

ESWS takes the approach of software as a service (SaaS) and encapsulates each step of ES analysis in OWS including all inputs and outputs. This allows for any point of the workflow to be modified or redirected into a new process before continuing and differs from other approaches that only allow for the consumption of initial inputs and publishing of final outputs via open standards. Despite the increase in computational overhead this has the advantage of exposing all possible avenues for change and provides a mechanism to integrate unexpected innovation. Furthermore, since OWS are APIs they are platform agnostic and do not require specific software or hardware for implementation and can be used with many existing resources.

3.4 Implementation

Given the potential benefits of ESWS, we developed a prototype (see Figure 3.1) and made it freely available (https://esws.unige.ch). The prototype uses the Python libraries Django, OWSlib, GSconfig, PyWPS, and InVEST, along with several standard libraries. This solution uses a custom-built Python based Django web application user interface to retrieve tabular data from a simple HTTP file server with a pseudo-TJS, retrieve and store spatial data on GeoServer with WCS and WFS via GSconfig, and execute ES software via custom processes in a PyWPS server with a WPS.

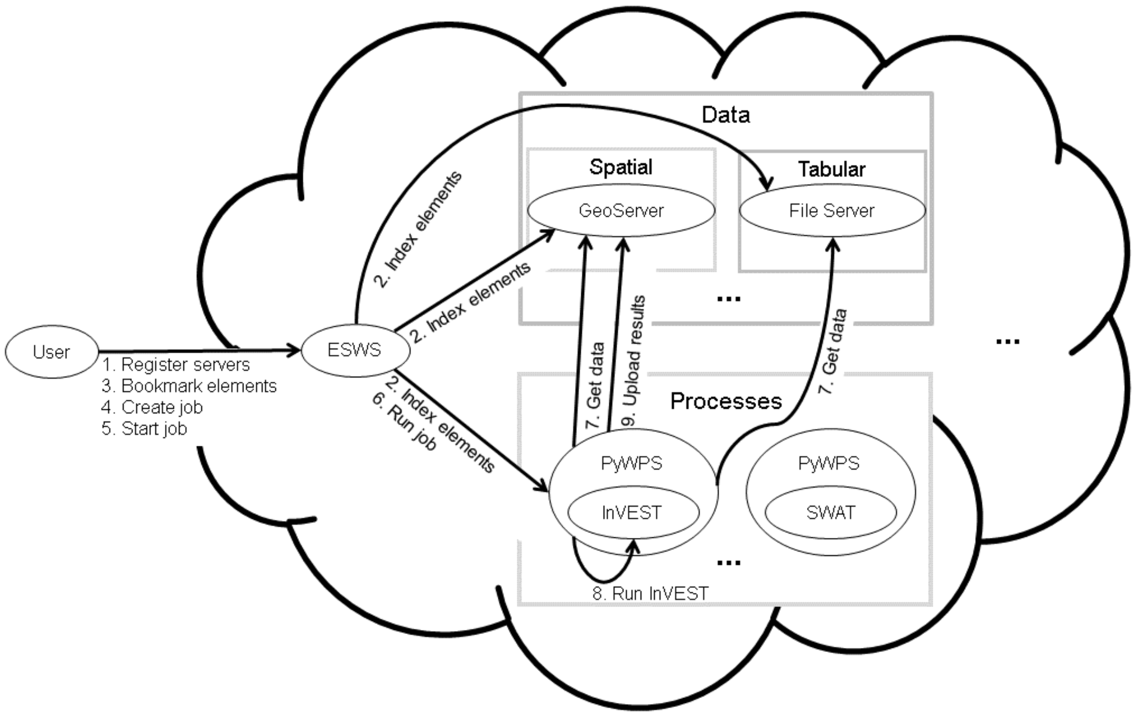

Figure 3.1 ESWS prototype architecture showing direction and type of requests for an InVEST model run

The prototype consists of four components: the frontend client, the tabular data server, the spatial data server, and the processing server (see Figure 3.1), each of which are independent and can be hosted on separate computers. Where possible, communication between these elements is done via OWS with representational state transfer (REST) commands and formatted URLs, which allows integration of new OWS compliant third-party components. The frontend client is a dashboard where servers are added, and their resources are automatically indexed (see Figure 3.2). For example, registering a WPS server will give a complete list of the WPS processes available which can then be bookmarked individually for quick use. A processing job can be created with those WPS processes, yielding a form where each tabular or spatial data parameter can be set using drop down boxes populated with the available OWS data (see Figure 3.3).

This separation between the user, data storage, and processing adds complexity but promotes data provenance. Since all changes are done remotely, the workflow is self-documenting and allows both the original scientist and any others granted access to examine and run it to produce results. Workflows can be iterated on by making small changes to each job such as applying a range of values to a parameter. This can be especially useful for sensitivity, specificity, and exploratory analyses. Results are stored remotely, making sharing a simple matter of user permissions. This combination of capabilities can facilitate collaboration by streamlining the sharing of data, processes, and results. This transition from data to results is preserved in a workflow that can be edited to incorporate updates to data or changes in the direction of analysis. Because ESWS requires the availability of a resource within a network in order to function, examining ESWS by the Nüst et al. (2018) criteria for reproducible research reveals that all criteria are satisfied at the highest or second highest level.

Local WCS

URL	http://127.0.0.1:8080/gs215/ows
Registrations	5
Jobs	0

Bookmarked Elements

Action	Id
Unbookmark	swatch21:ch_depth
Unbookmark	swatch21:ch_eto
Unbookmark	swatch21:ch_lulc
Unbookmark	swatch21:ch_pawc
Unbookmark	swatch21:ch_precip

Total: 5

Unbookmarked Elements

Action	Id
Bookmark	invest:depth_to_root_rest_layer
Bookmark	invest:eto

Figure 3.2 Screenshot of ESWS prototype WCS server details as specified by OWS results showing layers bookmarked for active use

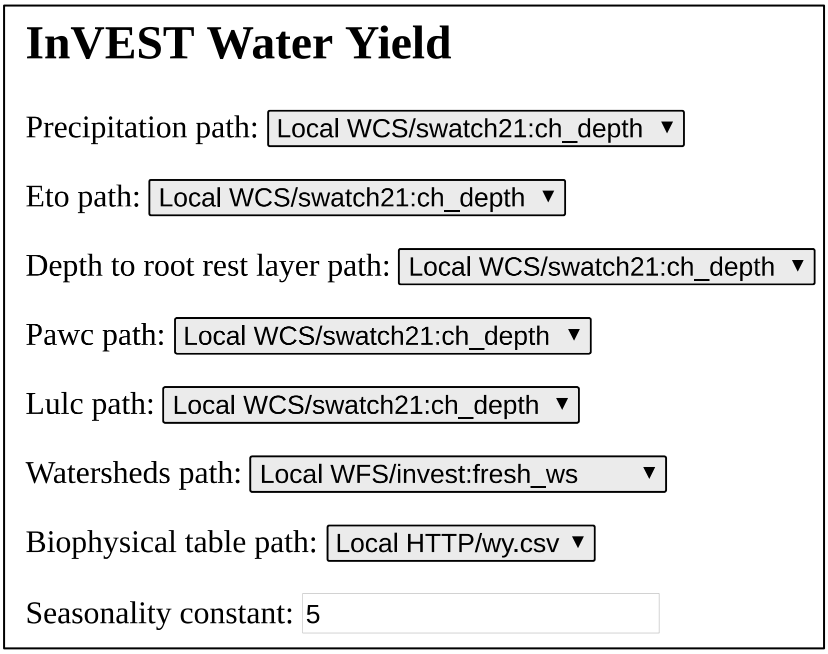

Figure 3.3 Screenshot of ESWS prototype WPS server job creation for InVEST Annual Water Yield showing automatic form generation as specified by OWS results with fields populated by bookmarked layers of the corresponding data types.

3.5 Average Annual Water Yield in Switzerland using ESWS

We demonstrate this approach using ESWS as an integral part of a hydrological study. Specifically ESWS is applied towards developing workflows for the SWATCH21 project (Lehmann et al., 2019) to research the links between eco-hydrologic processes and services with aquatic biodiversity in Switzerland, especially under climate change scenarios. These goals are particularly relevant for Switzerland, because while there are data-rich resources it can be difficult to gather the data and the provision of hydrologic services and impacts of expected environmental changes has not been studied at the national level. For this reason, average annual water yield is calculated with InVEST at the subbasin level to understand spatial variability. Understanding this spatial variability is important because it shows differences in water supplies to rivers and lakes that are essential for aquatic life. This is a good case study for ESWS because it uses user specified constants, tabular data, and spatial data in multiple formats that are stored on different servers. Furthermore, as data sources and methods for SWATCH21 are improved over time the corresponding ESWS workflows can be easily updated.

The InVEST water yield model is a water balance model that calculates average annual yield as the remainder from precipitation after transpiration, evaporation, and ground water recharge are allocated. The model requires raster data for root restricting layer depth, precipitation, plant available water content, average annual reference evapotranspiration, land use and land cover, and vector data for watersheds. These come from global coverage sources of the Harmonized World Soil Database (https://www.fao.org), WorldClim (https://www.worldclim.org/), ISRIC Soil Information System (https://www.isric.org), Global Aridity and PET Database (https://cgiar-csi.org), GlobCover (https://due.esrin.esa.int), and level 7 and 12 HydroBASINS from HydroSHEDS (https://hydrosheds.org), respectively. Additionally, a constant for precipitation seasonality and a biophysical table that contains the root depth and plant evapotranspiration coefficient for each land use land cover type are required.

After creating OWS resources with these data sources ESWS can be used to bring data and methods together to calculate average annual water yield with the InVEST water yield model. The steps (see Figure 3.1) consist of registering the OWS data servers and bookmarking the needed data sets (see Figure 3.2), generating and running an InVEST water yield WPS job with the appropriate parameters (see Figure 3.3), and manually visualizing the results (see Figure 3.4).

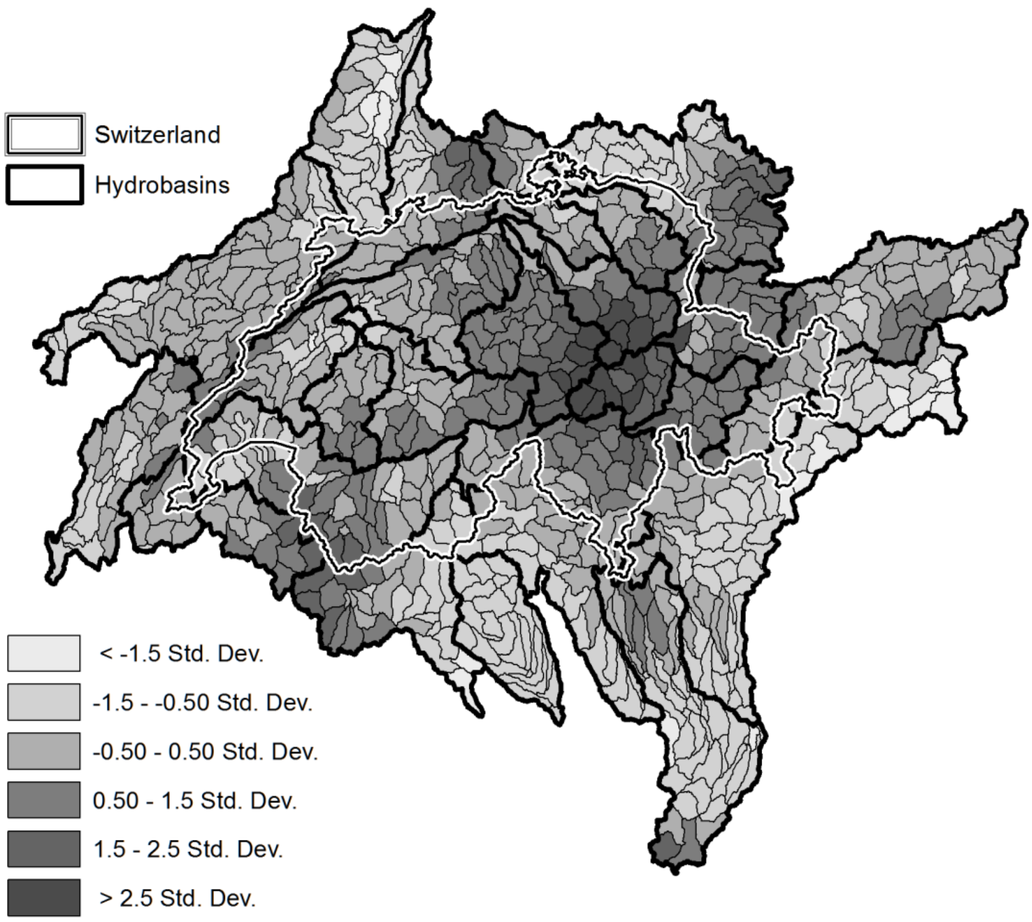

Figure 3.4 Water Yield per level 7 and 12 HydroBASIN in Switzerland.

3.6 Discussion

3.6.1 Added value of ESWS

ESWS represents a methodological improvement for ES assessment and a step towards improved digital scholarship by facilitating reuse of data, reuse of software, and provenance transparency (Gil et al., 2016) that is expected to primarily benefit professional scientists as the target users, but could also have impacts on policy makers, citizen scientists, and students. Like the shift to collaborative cloud-based document editing, ESWS benefits from similar advantages. The most obvious is the ability to collaborate throughout the analysis process with the inherent ability to share continuously at every step of the assessment. Each data transfer and model run are encapsulated within OWS calls that use remote inputs and produce remote outputs, both of which can be easily shared. This means that in addition to the primary user seeing intermediate data and preliminary results, all users that have been granted permission can see them and contribute to the assessment where appropriate.

The use of remote inputs and outputs means that the storage and processing of data is decentralized, and redundancies ensure protection against failures and performance scalability through distributed computing. A user of ESWS does not have to be concerned with backing up their data or the availability of resources for running hundreds of models because standard practices for server management can be leveraged to address these issues. For example, GeoServer's plugin to extend WPS with the Hazelcast computer cluster software (https://docs.geoserver.org/latest/en/user/services/wps/hazelcast-clustering.html) can be used to distribute and coordinate model runs.

Collectively the above aspects instill portability into ESWS workflows since all components are remote. This streamlines the preservation and curation of ES workflows making the ES assessment well documented and readily shareable. The preserved workflows can then be iterated on by changing individual parameters into ranges of values for calibration or for new scenarios and data sources. Furthermore, because OWS is used to connect every step of the workflow then any third-party data via TJS, WCS, and WFS, and third-party software via WPS can also be integrated. This could mean for example that an update to a land use land cover map could be simply swapped into an existing workflow by changing a WCS address or a new version of a software could be used by changing a WPS address, either of which would yield a new assessment. Fault tolerant job execution pauses the running of each job until all inputs are available, allowing a workflow to run in the required sequence. This same mechanism can be used to create a job for data that will be available in the future provided it will have a known address.

3.6.2 Modularity

The use of OWS between every step of analysis provides a mechanism by which improvements can be incorporated. These could be relatively simple things like model calibration batch runs, or more complex such as automatic data selection using semantic information. In the case of the latter, semantic information imbedded in a WPS process could be matched to the corresponding metadata of TJS, WCS, and WFS data sources and ease the manual selection of data with filters or even automatically select the most likely candidate data source (Nativi et al. 2013). The main principle however is that with a mechanism for openly integrating new components through OWS user needs can be dynamically met on an ad hoc basis with a standard API greatly simplifying implementation.

3.6.3 Data Provenance

As previously noted, there are many barriers to reproducibility. Several of these barriers share the common thread of data provenance, whether the problem is gaining access or ensuring that work is acknowledged and rewarded. ESWS addresses many of these concerns. The separation between user, data, and software enables user access control to address the main legal concerns by limiting the circumstances and manner of access. This technical solution can also be applied to allow unlimited access if desired. While academic culture issues are not addressed by a strictly technical solution, usage licenses can impose citation requirements and more generally the increased ability to share fosters greater collaboration, including with those trying to reproduce a study.

The ESWS approach does introduce issues of data, software, service, and workflow longevity. TJS, WCS, and WFS are well suited to addressing this concern by embedding data with its metadata and providing all the accessors needed to produce an archive of entire data sets, where practical, or only the relevant subset. Furthermore, metadata can be augmented with an embedded URL reference to additional information such as data provenance given in any form including useful domain specific formats like PROV and ISO 19115 (Jiang et al., 2018; Tilmes, C. et al., 2013). The OWS standard for software, WPS, cannot readily be used to archive WPS processes because they do not have accessors for copying and can functionally be a black box. Ideally a later version of WPS would include this functionality explicitly, but as an interim solution a URL for a virtual machine or container can be provided, as is the case with our ESWS prototype. For more information see the ESWS documentation (https://esws.unige.ch).

3.6.4 Technical limitations

The practicalities of ESWS implementation convey several limitations. The need for multiple libraries (e.g. OWSLib, PyWPS, etc.) to achieve the suite of OWS standards remains a vulnerability with an increased possibility for them to become incompatible. Most OWS have been expanded upon and have multiple versions, so the specific version a library implements means that the feature set supported between clients and servers may vary. This is especially the case for the WPS standard where version 2.0 supports nested inputs and outputs. These complications could be addressed by an OGC reference implementation, but that would then create a bias for a specific programming language or platform. As of this writing, the OWS libraries for ESWS have not gone through the OGC compliance and interoperability testing and evaluation process (http://cite.opengeospatial.org/) and therefore may lack compliance. WPS is a standard for running a process not for redistributing a process, and for true portability a method for distributing the algorithms and platforms is important (Peng, 2011). The incorporation of containers such as Docker, or package distribution methods such as the Python Package Index into ESWS could be useful as well as incorporating lessons learned from past initiatives such as the Cyberinfrastructure Shell (Herr et al., 2006).

Specific to the prototype are limitations from its distribution as a virtual machine, which is practical in that it is a turnkey solution, but this also limits performance. There is an ESWS installation script for Linux, but because of all the separate components the initial setup can be difficult. Regarding the user experience, the current ESWS user interface accessed via a web browser is spartan and documentation on creating new custom OWS servers is limited.

3.6.5 Future development

There are several areas in which active development of the prototype continues. This includes optimizations of existing core features like caching, server management, job queues, and access control, as well as improving upon existing integration of InVEST and other software like SWAT. In the case of InVEST, this is primarily about expanding support for optional parameters. As a proof of concept, a basic SWAT WPS server was also created. This allows the running of an existing SWAT model but does not incorporate any of the extensive preprocessing needed to create a SWAT model. Generally, it should be possible to encapsulate any model that can be run from a script into a WPS service, however complex models that require intermediate inputs that cannot be determined at run time might require the use of multiple interdependent WPS processes. Improving the import, export, and visualization of workflows in Business Process Model and Notation format is a priority as this has been shown to be very useful (Meek et al. 2016), the latter being critical for data provenance. This may be expanded into a graphical programming environment, but that is not currently a priority. Generally, further work will focus on improving the existing functions and the user experience with the platform, with an emphasis on meeting the needs of experts to curate their work.

3.7 Conclusions

The “reproducibility crisis” is an emerging concern in many disciplines including GIScience and, consequently, ecosystem services assessment. Lack of supporting tools has been identified as contributing to this challenge. Here, we have described an approach that offers a partial solution by supporting interoperability and enhancing data provenance. The heterogeneity of data and methods naturally leads to fragmentation, but interoperability by design can ameliorate this. While the integration of diverse data and methods is challenging, the underlying commonality of spatial data and spatial analysis means that interoperability is possible.

ESWS can readily combine existing software (e.g. InVEST and SWAT) with OWS to create a novel and timely method. Drawing on a deep understanding of InVEST and extensive software testing, we have overcome a key challenge for reproducibility and comparative analysis that result from the abridged descriptions of methods common to much of the ES and GIScience literature. Standardization of methods would further reduce these challenges and promote good science.

The value of ESWS goes beyond conglomerating software through a common API and user interface for computer and human resource efficiency. ESWS also offers the potential to create self-documenting workflows that can seamlessly share and publish results while maintaining user control over access. Such workflow models are reactive and respond to changes in inputs including the publication of new data and results from other models. Our expectation is that these improvements in accessibility will facilitate collaboration, curation, and dissemination. Ultimately, the hope is that this democratizes science and accelerates the progression from data to informed decision making (Lehmann et al., 2014, 2019).

Acknowledgements

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List of Acronyms

AGILE	Association of Geographic Information Laboratories in Europe
API	Application programming interface
ARIES	Artificial Intelligence for Ecosystem Services
ES	Ecosystem services
ESWS	Ecosystem services web services
FTP	File transfer protocol
GEOSS	Global Earth Observation System of Systems
GFCS	Global Framework for Climate Services
GIScience	Geographic Information Science
HTTP	Hypertext Transfer Protocol
HydroSHEDS	Hydrological data and maps based on SHuttle Elevation Derivatives
INSPIRE	Infrastructure for Spatial Information in the European Community
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
ISO 19115	International Organization for Standardization standard 19115
ISRIC	International Soil Reference and Information Centre
OGC	Open Geospatial Consortium
OPAL	Offset Portfolio Analyzer and Locator
OWS	Open Geospatial Consortium web services
PET	Potential evapotranspiration
REST	Representational state transfer
RIOS	Resource Investment Optimization System
SaaS	Software as a service
SWAT	Soil and Water Assessment Tool
SWATCH21	Soil and Water Assessment Tool project for Switzerland in the 21st century
TJS	Table Joining Services
URL	Uniform Resource Locator
WCS	Web Coverage Service
WFS	Web Feature Service

WPS	Web Processing Service
XML	Extensible Markup Language

Computer Code Availability

Name of code: Ecosystem Services Web Services (ESWS)

Developer: Martin Lacayo, enviroSPACE, Institute for Environmental Sciences, University of Geneva, 66 Bd. Carl-Vogt, CH-1205, Geneva, Switzerland, Martin.Lacayo@unige.ch, +41 22 379 08 62

Year first available: 2019

Hardware required: 2GB RAM, 8GB storage

Software required: VirtualBox 6+

Program language: Python

Program size: 2.1GB

URL: https://esws.unige.ch

4. DESIGNING LASTING ECOSYSTEM SERVICES ASSESSMENT TOOLS FOR THE SCIENCE-POLICY IMPLEMENTATION INTERFACE

This paper was submitted to *Ecosystem Services* in October 2022 and is under consideration.

TITLE PAGE

Journal: Ecosystem Services

Title: Designing lasting ecosystem services assessment tools for the science-policy-implementation interface

Martin Lacayo[1], Anthony Lehmann[2], and Louise A. Gallagher[3]

1.Corresponding Author, University of Geneva, Boulevard Carl Vogt 66, 1205 Geneva, Switzerland. Present address: Fachhochschule Nordwestschweiz, Bahnhofstrasse 6, 5210 Windisch, Switzerland,

2.University of Geneva, Boulevard Carl Vogt 66, 1211Geneva, Switzerland, anthony.lehmann@unige.ch

3.Louise Gallagher, University of Geneva, Av. de Mail, 1205 Geneva, Switzerland, louise.gallagher@unige.ch

HIGHLIGHTS

- Improving the science-policy-implementation interface (SPI-I) is a critical challenge.
- Ecosystem service assessment (ESA) tools can inform the SPI-I.
- Changes in software design and deployment would improve ESA tool longevity and benefit the SPI-I.

ABSTRACT

Ecosystem service assessments for successful science-policy-implementation interfaces require that software is findable, accessible, interoperable, and reusable (FAIR) over the policy timeline. The FAIR principles for research software, published in 2019, provide a framework for understanding the sustainability of software. Pairing FAIR with a 2018 study on the role of ecosystem services in the Sustainable Development Goals, we examine the longevity of prominent ecosystem service assessment software and identify opportunities for changes. Longer-lived ecosystem service assessment software will increase the return on investment by extending the time over which informed decision making is supported.

Keywords

science-policy-implementation interface, ecosystem service, software sustainability

4.1 INTRODUCTION

Understanding how to improve the relationships between science, policy, and practice is one of the critical challenges for sustainable development in the 21st Century (UNEP, 2012, 2017; UNDESA, 2015, 2019; ISC, 2021). We put a vast amount of faith and resources into improving the relationship between science and policy to instigate, guide, enable and evaluate sustainability transitions at differing scales (Köhler et al., 2019). Yet, there are widely differing views on the effectiveness of this investment stemming from a variety of perspectives. Strong statements have been made about how a “dynamic science-policy interface can be a core instrument to support well informed decision making” for environmental and sustainability outcomes (UNEP, 2017:1). However, we rarely test for the conditions needed for such interfaces to enriched decision making.

This long-standing puzzle (Gluckman, 2016) begs a better exploration of 1) what constitutes successful science-policy-implementation interfaces (SPI-I) in terms of decision support in critical areas of sustainability science and policy, 2) what is the state of the art of current decision support in critical areas of sustainability science and policy and 3) what is the distance between these and 4) what concrete improvements can be made. These are the questions explored in this chapter, with a focus on software-based ecosystem service assessment tools and their connection to policy and implementation decision making in the domains of biodiversity and sustainable development.

Biodiversity and ecosystem conservation is a paradigmatic example within which we can explore and learn about dysfunction and success for relationships between science, policy and implementation (Perrings et al., 2011; Pregernig, 2014). In particular, ecosystem services assessments are offered up as science-based tools to support biodiversity conservation policy and practice, especially as it intersects with development strategy, investment and implementation (Ruckelshaus et al., 2015). Among the important promises of ecosystem services assessments are support for decision making across spatial and temporal scales (Daily et al., 2009; Martínez-López et al., 2019). However, little scholarship has examined the prevailing practices of designing and distributing ecosystem service assessments for their capacity to actually deliver on their promise (Rosenthal et al., 2015). There is a need to identify what kind of failures are happening and why; and likewise, potential solutions where practice may fall short of promise.

The first two questions are addressed through literature review. The original research contribution of this chapter is to review the design features of current leading ecosystem services assessment tools and evaluate them in the context of the ideals advocated for the FAIR for software principles for the creation and stewardship of scientific software. The second key contribution is to propose concrete improvements that can be made in the next advances in software-based assessment decision support tools to meet basic conditions for contributions to policy and implementation.

4.2 LITERATURE REVIEW

4.2.1 What constitutes successful science-policy-implementation interfaces (SPI-I)?

Science-policy-implementation interfaces (SPI-Is) are "social processes which encompass relations between scientists and other actors in the policy process" (van den Hove, 2007). Organizations, initiatives or projects that work at the boundary of science, policy and society are most often recognized as facilitators of such processes, which in turn have a myriad of purposes and take many different forms and can include actors from across society (Bednarek et al., 2016; UNEP, 2017). One common underlying goal however could be defined as improving or supporting decision-making (van den Hove, 2007; Van Enst et al., 2014) so that decision makers are well-informed about the problem, the stakes in the problem, the range of available interventions to address it, and likely outcomes of each intervention (Pielke, 2007).

At the highest level, these processes are expected to facilitate the relationship between science, policy, and implementation in order to address global environmental change challenges like climate change or biodiversity loss (Colloff et al., 2017, 2017; Cornell et al., 2013; Ostrom, n.d.). At more grounded, operational level, expectations can perhaps be further refined using the three core objectives for sustainability science (Kates et al., 2001; Miller 2014): 1) to develop an understanding of the fundamental and complex interactions within society, across societies and between nature and society; 2) to support the design of policy and practice actions that will guide these interactions along sustainable trajectories; 3) to enable social learning necessary for widespread institutional change. If these objectives can be achieved, the hope is that sustainability science can support forms of good governance and management that feature large in sustainability theory (Armitage et al., 2009; Bennett & Satterfield, 2018; Berman et al., 2012; Folke et al., 2005) but remain rare in practice (Boyd et al., 2015; Chaffin et al., 2014; Partelow et al., 2020; Wyborn et al., 2019).

Actors in sustainability need help to connect and filter information, navigate complexity, and make effective, equitable and adaptive decisions with consideration of risks and impact for many different groups in society today and in future despite deep uncertainties (Bennett & Satterfield, 2018; Clark et al., 2016; Haasnoot et al., 2013). Biodiversity conservation policy and science illustrates how challenging an undertaking this is in practice. It is a complex, polycentric and multi-scale/level governance domain with a vast array of conflicting needs and contested values (Gavin et al., 2018; Matulis & Moyer, 2017; Reed, 2008) and implementation challenges over varying scales (Sterling et al., 2017). There is demand for science to help navigate biodiversity loss and conservation as a global problem with a myriad of local and regional manifestations (Loreau et al., 2006) - and even stronger calls for connecting 'knowing more' to 'doing better' over the past two decades (Brunet et al., 2018; Knight et al., 2008; Lindenmayer et al., 2013). Yet one of the repeating challenges in biodiversity conservation science and policymaking is overcoming the silo between disciplines and institutions, and practical expertise to generate information in support of good environmental governance and decision-making (Daily et al., 2009; Game et al., 2015; Koetz et al., 2011; Maas et al., 2019; Perrings et al., 2011; Rodela et al., 2015).

Scholar-practitioners have sought to address challenges and advance forms of knowledge co-production and governance that can generate equitable, effective and useable information (Guston, 2001; Turnhout et al., 2012, 2013; Tinch et al., 2016; Toomey et al., 2016; Nel et al., 2016). Recently, the dominant perspective of a linear relationship between science and policy – where science is valued largely for its separateness from politics and policy (Koetz et al., 2011) – is giving way to an increasing appetite for reimagining the role that more transdisciplinary science can play. Particularly in creating spaces where citizens, domain experts and policy actors come together to better understand challenges and goals in context and find acceptable, effective pathways for individual and collective action that bring about material improvements (Ban et al., 2013; Berkes, 2007; Gallagher et al., 2020; Knight et al., 2006; Reyers et al., 2010; M. Schut et al., 2013; J. C. Young et al., 2014). This perhaps is a good definition for general SPII success.

Yet, over 20 years of scholarship across diverse fields of Science and Technology Studies (Jasanoff, 2005, 2010, 2013), policy sciences (e.g. Weible et al., 2012; Richards, 2019); in planning and geography (Hesse, 2015; Hesse et al., 2019); environmental governance and management (Bryson et al., 2019; van den Hove, 2007; West et al., 2019) and climate change and biodiversity (Miller & Wyborn, 2018; Sarkki et al., 2015; Wyborn et al., 2019) have validated some basic success and failure factors. Clear objectives, appropriate inclusion, well-run processes, sufficient resources make positive differences (van den Hove, 2007; UNEP, 2017). Quality of 'fit' of knowledge production to the problem and context matters (Cash, 2003; Clark et al., 2016), and ensuring availability and access to research outputs (Brown & Farrelly, 2009; Gerritsen et al., 2013; Gibson et al., 2017). Above all, trust between information producers and users is critical (Kirchhoff, 2013; Ostrom, n.d.) as is the credibility, saliency and legitimacy of information produced (Cash, 2003). Consideration and understanding of pragmatic issues like bureaucracy, political acceptability and technical feasibility, process timeframes and being flexible and ready to move with timing of events is also essential (Cairney, 2019; Dunn & Laing, 2017; Woods & Gardner, 2011). Indeed, matching timing and objectives between policy-making and the scientific process, policy actors' research skills; and available budgets are another set of practical considerations (Borowski & Hare, 2007; Chambers et al., 2022; Lang et al., 2012; Sarkki et al., 2015). Lang et al., (2012), Sarkki et al (2015) and Chambers et al. (2022) among others, have stressed the concept of iterativity as critical because it allows for improvement across all these factors.

4.2.2 What is the state-of-the-art of ecosystem services assessment tools?

Ecosystem services assessment (ESA) is intended to provide information about the benefits humans receive from nature (Häyhä & Franzese, 2014), often with the explicit goal of integrated decision support to multiple and varying projects and users (Dang et al., 2021; Harrison et al., 2018; M. Ruckelshaus et al., 2015).

Diverse methods have been used to conduct ecosystem services assessments from mapping, modeling, and economic valuation (Dang et al., 2021; Ferrier et al., 2016; Häyhä & Franzese, 2014; Mandle et al., 2016). Where have we come from? Where are we today => emphasis on model-based approaches and why this is the case.

Vast resources have already been dedicated to developing these approaches, models and tool kits, including public funds through direct government procurement and support to national and international research (Martinez-Harms et al., 2015). The importance of publicly available ecosystem service assessment tools for evaluating potential impacts of sustainability policy actions, particularly for the for the 2030 Agenda for Sustainable Development, have been noted for three main reasons.

1. ESA supports the type of systems analysis required for identifying interventions with payoffs across multiple sustainability objectives. There is a many-to-many relationship between ecosystem services and the types of outcomes desired under the Sustainable Development Goals (SDG) targets. That is, improved management in a single ecosystem service can contribute to multiple SDGs being achieved. Likewise, a single SDG target may require multiple ecosystem services to be secured (Fig. X). This one-to-many relationship is the argument for an integrated modelling approach whereby multiple ecosystem services are simultaneously modeled so that SDG targets are addressed in concert.
2. Policy and implementation strategic analysis, monitoring and evaluation is costly and as noted *"a large number of modelling tools are already available to support policy-makers in their efforts to incorporate ecosystem service approaches, which can increase the chances of achieving the ambitions set out in the SDGs."* (Wood et al., 2018, p. 18).

3. ESA tools are most often developed as software intended for an individual project, though some are more generalized for implementation across different study areas. The Natural Capital Project’s InVEST software, as one example, has been used to assess water yield, carbon storage, and coastal protection in regions around the world (Lacayo et al., 2021; M. Ruckelshaus et al., 2015). Adapting generalized ecosystem services assessment software for project specific assessments requires substantial investments in expertise and time (Mandle et al., 2016) but continues to be a common approach because of its potential value to support informed decision making quickly and cost-effectively (Martinez-Lopez et al., 2019).

4.2.3 What is the potential distance between conditions for successful SPII and the current state of the art in software ESA?

There many open questions regarding the state of relationships between modelling science, policy and implementation actions, with many efforts underway to address these. For example, empirical experience indicates that information provided by much environmental decision-support science - not just ecosystem services assessments - is often not available, usable, nor used effectively (Bhave et al., 2016; McIntosh et al., 2011; Pannell et al., 2018; K. Young et al., 2002). Biodiversity and ecosystem service information and knowledge utility has been noted as hard to discern and evaluate (M. Ruckelshaus et al., 2015; Sitas et al., 2014). Despite many proponents and much effort, examples of success stories remain infrequent and largely undocumented and clarity on how available ESA tools guide decisions, or not, in practice is needed (Ban et al., 2013; Dang et al., 2021; Martinez-Harms et al., 2015). One observation is that this science is often not produced to meet the needs and realities of robust, daily ecosystem management practice under conditions of complexity and deep uncertainty (e.g. Feger et al., 2019; Gibson et al., 2017). Increasingly important is the many uncertainties and plural values in finding and negotiating sustainability and resilience - these have been poorly considered in past valuation pursuits at times but is now a cutting edge in theory and methods advancements (e.g. Colas et al., 2020; Gunton et al., 2022). More general issues of polititization of science, scientific replicability and open science issues are important factor too (De Smedt et al., 2020; Gould et al., 2020).

It seems likely that distance between conditions needed for successful SPII relationships and outcomes and ESA best practices is a live challenge for many reasons. However, one particular issue crops up in various forms across recent literature on SPII success factors and critiques of software-based ESA that relates to, and even underpins many of the above issues: **the capacity of ESA modelling software packages to be used in policy and implementation decision making over long-term timeframes.**

While no systematic evaluation of this characteristic currently exists at the time of this research, previous studies point to number of aspects concerning longevity of ESA software tools. The ability to evaluate biophysical change over long timeframes is critical. Social and ecological interactions and change is not uniform over space and time, and neither are the 'windows of opportunity' to influence policy (Cairney, 2019) nor effects of policy interventions (Cairney, 2019, 2021). The spatially explicit nature of biophysical-oriented ESA software tools means that existing geographic information systems are well suited to addressing distribution problems and understanding how policies may play out from place to place is a primary goal of ecosystem services assessment software. Software-based ESAs are particularly important because they can support analyses that compare policy outcomes over a range of places. It is especially useful if an analysis can also occur over an extended time period allowing reassessments over time as new information becomes available. Revisiting an analysis does however require that ecosystem service assessment software is itself available over time. Process timeframes also matter for use in decision support. Ideally, ecosystem services assessment studies are "part of an iterative science-policy process" (Ruckelshaus et al., 2015, p. 11) that actively engages stakeholders (Dang et al., 2021; Rosenthal et al., 2015), and contrasts the distribution of ecosystem services costs and benefits to different beneficiaries under comparable management options (Dang et al., 2021; Mandle et al., 2021) on an ongoing basis. Finally, evaluation of the utilization and contribution of ecosystem services assessments may only be evident where use is long term and monitoring goes beyond project timeframes alone (Ruckelshaus et al., 2015).

Currently, this time requirement for effective contributions to SPII is not guaranteed because of the issue of abandonware and fleeting models in software development, which in turn represents risks for ESA model longevity. *Abandonware* is software that no longer has official support available (List et al., 2017). This often means that it is no longer distributed or supported by the developer or copyright holder, though at times communities can emerge spontaneously to fulfill this role (e.g., AmbioTEK supplying Co$ting Nature, see Findings for more details). *Fleeting models* are ideas introduced publically in an immature state, for example at a conference presentation, but then are ultimately abandoned without publication. Abandonware and fleeting models compromise the analytical environment for meaningful long-term science-policy decision-support. And, to date, we do not have a comprehensive overview of how serious this issue is for ESA though some work is advancing for data analytics generally (e.g. De Smedt et al., 2020). This paper identifies abandonware and fleeting models among even prominent ESA tools.

Two core enabling conditions for SPIIs to function well are trust and potential for iterativity, and both require time - including particularly the opportunity for participants to build confidence in analytical support systems. Some of the analytical value proposed by spatially-explicit ESA models is the modelling of biophysical change over time. Learning about ESA performance in real world "murky" policy contexts (Woods & Gardner, 2011) requires time. Based on these observations, we assume that design for permanence is one basic, minimum criteria for ESA software tools to be effective in supporting informed decision making and focus our explorations regarding distance between the ideal and the actual on this particular factor. Understanding the reliability aspect of software-based ESA is critical given the hopes being placed in existing tools for securing progress on Agenda 2030.

4.3 METHODS AND MATERIALS

4.3.1 Approach

We take a case study approach to explore if current state-of-the-art ESA software packages meet the basic condition of being available over time with long-term capacity to inform policy making.

4.3.2 Case study selection

The tools identified by Wood et al. (2018) is a comprehensive overview of existing software suites that constitute the state-of-the-art ecosystem services assessment applications. Using a novel, mixed methods approach the authors solicited expert opinion to identify key combinations of ecosystem services and SDG targets with clear environmental elements. Their results found 178 ecosystem service – SDG target combinations with high importance as “focal points for policy action” (Wood et al., 2018, p. 73) to realize 41 SDG targets, especially those related to provisioning of food and water and maintenance of habitat and biodiversity under SDG2 Zero Hunger, SDG14 Life Below Water, and SDG15 Life On Land. They then identified tools for evaluating synergies and tradeoffs between ecosystem services with potential to make strong contributions to achieve the identified SDG targets and evaluate “the impact of a planned intervention at the landscape scale” (Wood et al., 2018, p. 77). These tools were screened to determine whether they addressed multiple ecosystem services at landscape scale or larger, were publicly accessible and could be used without a proprietary product, were not specific to a single geography or land use/land cover type, and were spatially explicit. Based on these criteria, they identified 23 modeling tools, including 12 ecosystem service models with ease of use ranging from low to high.

Of these 12 ESA tools, we evaluate 11 of these for the long-term capacity of these software packages to inform policy making (Table Z). We do not include ARIES in our evaluation because it is incomparable to the other tools. It is a semantic web intranet run on the k.Lab platform composed of a network of distributed nodes with resources published by certified partners. End users use nearly natural language to access resources that include static data and dynamic computations. Semantic webs have the potential to revolutionize the way ecosystem services assessments are conducted and how the resulting information is organized. However, the focus of this paper is ecosystem service assessment tools, *per se*, and how their longevity impacts policy objectives. If the proposed solutions in the discussion became standard practice then in addition to other benefits the integration of compliant tools into ARIES would be streamlined.

4.3.3 Evaluation criteria

We evaluate the current status of the case software-based ESAs using the FAIR for software principles.

The findability, accessibility, interoperability, and reusability (FAIR) guiding principles for scientific data management and stewardship were first proposed by Wilkinson et al. (2016) and later revisited by Lamprecht et al. (2020) for application to research software, providing detailed rephrasing, reinterpretation, and extension of the principles in the new context. This revision is called FAIR for software.

A key consideration of the FAIR for software framework is the concept of software as a dynamic product of a changing software ecosystem. For example, unlike typical data, software requires frequent changes (Lamprecht et al., 2020) to keep pace with updated libraries and deprecated platforms. While subject to the same dynamics as research software writ large, our focus is more narrowly constrained to ecosystem service assessment software in the domain of geosciences and specifically falls under the ecosystem services assessment category of mapping. For this reason, a selection of the most relevant criteria were made (Table 4.1).

Table 4.1Selected FAIR for software principles for evaluation criteria. (Adapted from Lamprecht et al., 2020)

FAIR Component	Principle Code	Principle
Findable	F1	Software and its associated metadata have a global, unique and persistent identifier for each released version.
	F4	Software and its associated metadata are included in a searchable software registry.

Accessible	A1	Software and its associated metadata are accessible by their identifier using a standardized communications protocol.
	A2	Software metadata are accessible, even when the software is no longer available.
Interoperable	I4S	Software dependencies are documented and mechanisms to access them exist.
Useable	R1.1	Software and its associated metadata have independent, clear and accessible usage licenses compatible with the software dependencies.
	R1.3	Software metadata and documentation meet domain-relevant community standards.

Criterion 1: The software must be identified and a potential provider located. In FAIR for software this is called "findability" and is the ability to find metadata about the software.
Indicator: An internet search yields an acronym (if available), long form name, and version number (F1); an official URL, third party URL, and/or code repository (F4).

Criterion 2: The software must be obtainable from the provider. In FAIR for software this is called "accessibility" and is the ability to retrieve the software .It should be noted that in the FAIR for software principles a distinction is made between (F4) having a record about the software, and (A1) having a standard protocol for accessing the software. In our case, we rely on URLs, which specify both the location of the record and method of access.
Indicator: An internet search yields an official URL or code repository (as in F4), and access protocol (A1); and a third party URL or code repository (A2, also as in F4).

Criterion 3: **the software must run.** In FAIR for software this is called "interoperable" and is the ability to use the software.
Indicator: The source code is compilable (if available), installer runs, and software starts. This requires at a minimum, but is not limited to, access to all software dependencies, required platforms, and license or authorization keys (I4S).

Criterion 4: the software must meet the needs of ecosystem service assessment workflows. In FAIR for software this is called “reusable”.
Indicator: The software licenses, especially the terms of use, and whether or not redistribution of the software is possible (R1.1, R1.3) and that there is a documented command line interface (CLI), scripting environment, or application program interface (API).

4.3.4 Scoring framework

In order to rank the relative FAIRness of the tools, I created a scoring mechanism for each of the identified variables (Table 4.2). One point was awarded if the variable had a value, and zero points were awared if the variable had no value. The variables for an acronym and long form name were collapsed to yield a score of either zero or one. The variables for an official URL or a third party URL were collapsed to yield zero or one. I then added up the total sum for each FAIR for software principle and normalized the scores to fall between zero and one. I then added up the total sum for each FAIRness component and normalized the score to fall between zero and one. In other words, each score weights the seven FAIR for software principles equally within each individual FAIR component, but due to differences in the number of variables for each principle there is a small difference in weighting for accessibility.

Table 4.2 Weighted scoring for evaluating the FAIRness of tools

FAIR Component	Principle Code	Variables	Principle Weight*	Component Weight*
Findable	F1	Acronym or long form name Version number	1/2	1/4
	F4	Official or third party URL Code repository	1/2	
Accessible	A1	Code repository Access protocol	1/2	1/4 1/4
	A2	Third party URL	1	1/2
Interoperable	I4S	Compilable Runnable	1/2	1/2
Reusable	R1.1	License Redistributable	1/2	1/4
	R1.3	Command line interface (CLI) Application programming interface (API)	1/2	

*Weights are expressed as fractions in order to avoid irrational numbers.

Our analysis necessarily has some limitations. We only evaluate tools identified by Wood et al. (2018) and the selection criteria (see above), while rigorous, are likely restricted to tools published in the English language with a presence in literature or on the web. The FAIR for software guiding principles are based on the FAIR guiding principles for scientific data management and stewardship and sometimes feel a bit over specified. For example, the distinction between finding that metadata exists and being able to examine the metadata may be less important for software than it is for data in the current era. Nevertheless, the FAIR for software principles are concise and measurable, collectively addressing the most important aspects for the reuse of scientific software in a way that may prove to be prescient.

4.4 FINDINGS

Findings from our evaluation of software for the 11 tools identified by Wood et al. (2018) demonstrate considerable variability in their fulfillment of the principles of the FAIR for software framework (Table 4.3, Figure 4.1), a status we will refer to from here on as their FAIRness. FAIRness is cumulative. That is, progress through the components of FAIRness depends on all previous components having been fulfilled. Thus, to be accessible, software must be findable. To be interoperable, it must be accessible and findable. Finally, to be reusable software must be interoperable, accessible, and findable. In the remainder of this section, we report the results of our evaluation of the FAIRness of these 11 tools. The reported status of software is current as of 30 July 2022. More detailed information on our analysis is available in supplemental materials.

Table 4.3 Tools are placed in the FAIR for software category that they at most fulfill by meeting the specified guiding principles. As a tool moves to the right it also fulfills all of the categories to the left. FAIR for software guiding principle codes are noted in parentheses. See Methods for category definitions.

Findable (F1 or F4)	Accessible (A1 or A2)	Interoperable (I4S)	Reusable (R1.1 or R1.3)
BLOSM*	CLIMSAVE	OPAL	InVEST
LandscapeIMAGES*	Co$ting Nature		SolVES
SERVES**	RIOS		UFORE/i-Tree Eco
Wildlife Habitat Benefits Estimation Tool*			

* No longer available. **Not publicly available.

4.4.1 Findable tools

Findable tools (FAIR for software principles F1 and F4) are unambiguously identifiable and listed in search indexes (Table 4.2 Weighted scoring for evaluating the FAIRness of tools). Four tools fulfill only the findable principles used in our analysis. The official URL for BLOSM (http://blosm.ornl.gov/) no longer works and the software appears to no longer be available. An academic paper (Parish et al., 2012) provides metadata about the software. Similarly, LandscapeIMAGES is listed on a third party website (https://peoplefoodandnature.org/tool/landscapeimages/), but the URL links to now defunct resources. An academic paper (J. C. J. Groot et al., 2007) provides metadata about the software. There is some indication that LandscapeIMAGES may have used Google services for hosting and could have fallen victim to a discontinued product. In 2016, Google Code Project Hosting was shut down and while there is an archive available (https://code.google.com/archive/d/code.google.com) LandscapeIMAGES does not appear to be in it. SERVES is not publicly available but still appears to be actively used as recently as 2020, as indicated by the non-profit organization Earth Economics. The software appears to be cloud based and would therefore use a potentially large amount of remote resources and is "accessible by Earth Economics team members only" (https://www.eartheconomics.org/serves). The Wildlife Habitat Benefits Estimation Tool was released by the non-profit Defenders of Wildlife (https://defenders.org/), but appears to no longer be available from them. It is listed on LandScope America (http://www.landscope.org/explore/ecosystems/ecosystem_services/defenders_benefit_toolkit/1/), a collaboration between the non-profits NatureServe and the National Geographic Society but links back to Defenders of Wildlife.

Table 4.4 Acronym and long form names of evaluated ecosystem services assessment tools' software

Software Program Acronym	Long Form Software Program Name
BLOSM	Biomass Location for Optimal Sustainability Model
CLIMSAVE	Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe
-	Co$ting Nature
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
LandscapeIMAGES	Landscape Interactive Multi-goal Agricultural Landscape Generation and Evaluation System
OPAL	Offset Portfolio Analyzer and Locator
RIOS	Resource Investment Optimization System
SERVES	Simple Effective Resource for Valuing Ecosystem services
SolVES	Social Values for Ecosystem Services
UFORE/i-Tree Eco	Urban Forest Effects model
-	Wildlife Habitat Benefits Estimation Tool

4.4.2 Accessible tools

Accessible tools are available from first and/or third party websites as downloads or server hosted applications (FAIR for software principles A1 or A2). Three tools are findable and also fulfill one of the FAIR for software accessible principles. The official URL for CLIMSAVE (https://www.climsave.eu/climsave/outputs.html) is working but the final output, the Integrated Assessment Platform (http://82.76.32.108/IAP/), was designed with the Microsoft Silverlight application framework that reached its end of life in 2021 and, therefore, can no longer be used. Co$ting Nature version 3.x is made available by a third party, AmbioTEK community interest company, through a website (http://www.policysupport.org/costingnature) on a non-commercial freemium basis or through partnering. There is extensive documentation, however, no source code or programmatic access appears to be available. RIOS version 1.1.16 (https://naturalcapitalproject.stanford.edu/software/rios) has been "retired" but is still available as Python 2.x source code (https://github.com/richpsharp/rios-deprecated). Python 2.x reached its end of life in 2020.

4.4.3 Interoperable tools

Tools are interoperable when everything needed to use them is documented and available and they can be run locally or through a remote server (FAIR for software principle I4S). Just one of the tools in our analysis is findable, accessible, and fulfills the relevant interoperability standard (I4S) but is not reusable. OPAL version 1.1.0 is available as a installer (https://naturalcapitalproject.stanford.edu/software/opal) and as source code (https://github.com/natcap/opal). It does not appear to be compatible with Windows 10 or later. It was written in Python 2.x, which reached end of life in 2020.

4.4.4 Reusable tools

Reusable tools can be run because licenses authorize them and doing so produces intelligible outputs (FAIR for software principles R1.1 and R1.3). Three of the tools we evaluated are reusable (i.e., they fulfill FAIR for software principle R1.1 or R1.3). To do so, they are also findable, accessible, and interoperable. InVEST version 3.10.2 is available as an installer (https://naturalcapitalproject.stanford.edu/software/invest) and as source code (https://github.com/natcap/invest). It is released under a BSD 3-clause license allowing redistribution in source and binary forms with or without modification provided the Natural Capital Project copyright notice, software license, and release from liability is maintained. There is a command line interface (CLI) and an application programming interface (API). SolVES version 4.1 is a plugin for the QGIS application (https://www.qgis.org/) and available as an installer (http://solves.cr.usgs.gov/) and as source code (https://code.usgs.gov/solves/solves-4.0). The source code contains some Python byte code. It is released under a Creative Commons CC0 1.0 license relinquishing copyright and material into the public domain (Creative Commons, 2002) and allowing all use, including redistribution, without limitations. Within QGIS, the Python Console allows for programmatic interaction with SolVES, but there does not appear to be any documentation to support its use. UFORE/i-Tree Eco version 6.1.40 is available as an installer (https://www.itreetools.org/eco/) after registering. It is released to the public domain, allowing for redistribution, but requires attribution and agreement that input data “will be public-domain data that can be used and distributed by other groups”. However, data can be requested to remain private, but a determination will be made on a case-by-case basis. There does not appear to be a CLI or API. It should be noted that i-Tree Eco requires an internet connection.

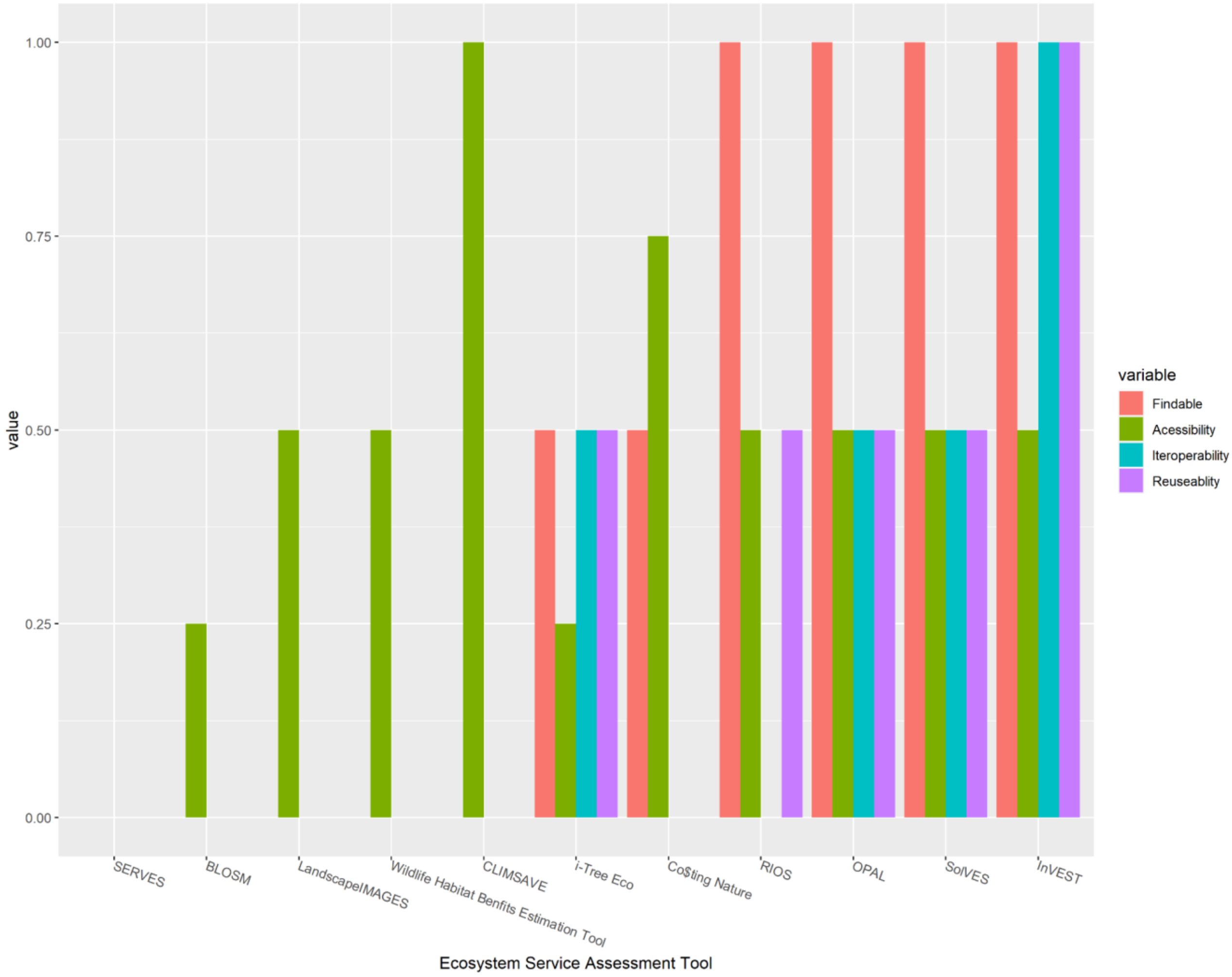

Figure 4.1 FAIRness profiles of software for evaluated ecosystem services assessment tools

4.5 Discussion

The current best understanding we have of SPIIs is that long term functioning is a core enabling conditions for SPIIs to perform. The current state-of-the-art spatially-explicit ESA software packages propose both scientific and policy contributions because, in theory and design, they allow for modeling of biophysical change over time, emphasize best practices in open science that seem important for long-term capacity. The results reported above indicate some serious distance between the ideal and the current best practice in existing ESA software when it comes to designing for long term capacity.

Longevity at the science policy implementation interface needs to be baked into the design, protocols, platform design for tools to be used in interfaces from the start. Our findings hint at some core technical considerations that could be overlooked. The following discussion is necessarily technical, but our intent is for it to be useful for programmers, scientists, and decision makers alike, as well as to provide guidance on hiring and design decisions to ultimately improve the FAIRness of existing tools.

4.5.1 The basic barriers to longevity

As noted in Methods, the analysis focused on seven FAIR for software principles (i.e., F1, F4, A1, A2, I4S, R1.1, and R1.3), which are nested under the four components of FAIR (i.e., findable, accessible, interoperable, and reusable). These principles are especially relevant to the resiliency of workflows and its impact on policy. There are some key differences between the challenges to FAIRness in desktop software and those of web based software. For example, web based tools tend to be highly findable and accessible and less likely to be interoperable or reusable. The differences between desktop and web based software can be captured by a variety of variables but the most relevant here are their architecture and hardware requirements. Architecture is like an ecological niche that determines the way and extent to which software occupies certain areas. For example, software might be stand alone, a solitary entity that exists within an isolated environment like a Galapagos tortoise (*Chelonoidis niger*). Alternatively, software might be distributed across a network like Pando, the quaking aspen tree (*Populus tremuloides*) that occupies more than 40 hectares in Utah, USA. Hardware is like resources that are required for survival. The tortoise requires food to be relatively close, while the aspen tree survives because it is distributed over a large area. The requirements to preserve each of these vary significantly. The choice of programming language and any application framework can have a big influence on the way software is packaged and how it is delivered. This choice is driven by engineering requirements but is often also influenced by the background of the programmer. These design decisions can contribute to the problem of abandonware. Even with the best of intentions, the selection of a platform for the application framework that becomes obsolete can render even the most substantial efforts unusable. The frequency with which platforms are discontinued argues for the use of protocols. Protocols for exchanging data and metadata directly support the FAIR for software principles as community standards. Embracing FAIRness even at a late stage in development can have a significant impact on the lifetime of software.

A resilient workflow is a workflow that uses at worst semi-permanent components and any need to accommodate a change in a data source or method can be done with minimal modification. There is a real need for resilient workflow considerations in the choice of ecosystem services assessment tools to inform the SPI-I. The selection and application of a tool takes the analysis down a path that is usually locked to the selected tool. Switching from a selected tool can be prohibitively expensive in terms of time and money, threatening the success of a study. While some risks to a project can be hard to predict, given the often unknown funding cycles and nature of commercial and academic enterprises, hardening analysis with an intentional approach to resilient workflows offers reduced risk and more flexibility if software unexpectedly becomes unusable. This is accomplished through the use of standardized protocols that can liberate resources at the initial workflow set up and any data or method changes that occur, especially during a long term study. Tools that use standardized protocols both in the distribution and functions of the software are in a better position to meet the needs of SPI-I.

The challenges for findable, accessible, and interoperable software tend to concern locating, decoding, and contextualizing information, respectively, while challenges for reusable software relate to limited permissions, metadata, and documentation. With an understanding of the technical context, the ontological framework of FAIR for software, and the need for resilient workflow considerations in the SPI-I, we discuss in detail each component of FAIR, the most relevant problems, and several solutions (Table 4.5).

Table 4.5 Common challenges to FAIRness in ecosystem services assessment software and solutions that promote resilient workflows.

	Problem(s)	Solution(s)
Findable	1. Record not listed	• Distinct name with version # • Software repositories • Publicly listed source code
Accessible	2. Record not legible	• Publicly accessible source code • 3rd party websites • Metadata standards
Interoperable	3. Record references missing	• Installers • Containers for development • Open source dependencies
Reusable	4. Permission limited 5. Metadata insufficient 6. Documentation limited	• Standard licenses • Metadata standards • Documentation generators

4.5.1.1 Problem 1: Record not listed

As a first step, software must be unambiguously identifiable (i.e., findable). To be identifiable, it must be possible to know the software's long form name and acronym, if used, as well as its version number. When any of these is missing it can be difficult to be certain whether or not you have found a record for the relevant software. Records can be located in general search indexes, domain specific search indexes, or software or code repositories and, ideally, would be in all of them. Being findable is the most basic and essential starting point for FAIRness. In our analysis the long form names of the tools we analyzed here were not difficult to find. However, this is not always the case. The version number of desktop software is usually specified, but for web based tools often it is not. It is essential that web based tools always include a version number and display it prominently. Increasingly, code repositories for desktop software are available but, unfortunately, this is not always the norm and it is even less commonly so for web based tools. These differences between desktop tools and web based tools are sometimes the result of the choice of programming language and language specific resources available from online communities. For example, InVEST is mostly written in Python and the developers decided to publish it to the Python Package Index, a well known resource for Python packages. On the other hand, CLIMSAVE was likely written in one of the .NET languages C#, F#, or Visual Basic, a requirement for the Silverlight application framework and, therefore, is not available on the Python Package

Index. Increasing the visibility of software through at least listing the details of source code (i.e., date, authors, programming language, dependencies, etc.) can be accomplished without the actual source code being provided. For example, the US Geological Survey Public Project Explorer (https://code.usgs.gov/usgs/project-explorer) lists publicly released USGS software products and links to but does not contain the actual source code of those software products.

4.5.1.2 Problem 2: Record not legible

Accessible software must have metadata that is clear, precise, and understandable. The protocol for decoding metadata is usually implied by the source. Metadata should be available from primary sources and also, as a contingency, from secondary sources. Metadata is most often available in an unstructured form, a minimal requirement, but much better is when it is provided in a structured format. When source code is made available it typically contains high levels of structured metadata. Unfortunately, in many instances, primary sources stop being available within a few years of creation and secondary sources often lack crucial details. At times it may be difficult to fully decode metadata, especially due to differences in international notation or localization. To the best of our knowledge the phenomenon of metadata being available but not able to be decoded due to an unknown protocol is not a widespread problem. In the future, however, the problem of indecipherable metadata could become a problem, especially for remote and isolated systems such as those on satellites.

In the best of cases, source code is made available to understand the precise implementation of each and every function and, furthermore, allows for complete scientific scrutiny. The burden of supplying and maintaining infrastructure to host source code is best outsourced to increase accessibility. There are many general source code hosting services (e.g., GitHub, Bitbucket, etc.) and specialized software repositories (e.g., PyPI, CRAN, etc.). Use of such repositories increases the visibility of software and provides a third party contingency for accessibility. These platforms use well documented and public protocols, and while many versions have been depreciated or superseded, we are unaware of any protocols that are no longer usable. At this level of FAIRness it is only about the ability to decode metadata, with no obligations to being open source. It seems reasonable that all projects, especially publicly funded projects should strive to meet at least fulfill the accessible level of FAIRness by making metadata and source code readily available, with guidelines for metadata applying equally to desktop and web based tools. We acknowledge that there can be a justifiable security concern when it comes to hosting web based tools, which inclines some developers to hide their implementation details in the hope that they will achieve security through obscurity. However, this is a fallacy and results in software that is inaccessible even while black hat hackers can easily automate launching a library of security exploits without needing to know details of the underlying system. A wide range of third party websites and version control platforms (e.g., Software Heritage [https://www.softwareheritage.org/], Onto Soft [https://www.ontosoft.org/], and Zenodo [https://zenodo.org/]) can preserve access to software, serving as an archive even when a project is discontinued or otherwise becomes unavailable. Metadata standards include ISO 19115, ISO 19139, Content Standard for Digital Geospatial Metadata (CSDGM).

4.5.1.3 Problem 3: Record references missing

Interoperability is a significant stumbling point for software. Interoperable software must list all its dependencies and suggest a mechanism for obtaining them. Desktop software is typically bundled with most, if not all dependencies, although these are sometimes fulfilled through a separate installer. Web based software typically handles all dependencies on a server, remote from and opaque to the user, with a network providing the majority of resources needed. In both cases, a third party dependency can become discontinued or unavailable, presenting a significant challenge to use of the software. Distributing stand alone software is often as simple as sharing an installer file. Distributing a web based tool, as opposed to simply providing use of a tool, requires duplicating or simulating the components and structure of the host network and is rarely done. This is clearly the reason why web based tools are generally provided as a hosted resource. Such complexity of distribution tends to render the lifetime of desktop software more enduring than that of web based software, which can cease to function the moment a server is turned off.

Dependencies and the mechanism to obtain them in order to achieve interoperability can come with financial and human resources costs. Beyond questions of social equity, these uptake costs can affect interoperability, and in some cases, be prohibitively expensive, as the current microchip shortage makes apparent. This is an area where web based tools have an advantage, with significantly lower costs and resource requirements for users. Web based tools shift the burden of setup and providing resources for the running of software from the user to the provider. This can make software and dependencies, which might otherwise not be installable, available to a user. Running software on web platforms also has the added advantage of accommodating cases where datasets are impractically large to distribute or restricted by data licenses.

At the most basic level, challenges to interoperability can take the form of undocumented software dependencies. At a more significant level, some dependencies can become unavailable because they rely on third parties. Depending on the level of complexity, software dependencies may themselves have dependencies that are no longer available. Chains of dependencies can cause a domino effect, cascading software into an unusable state. A danger for web based tools is link rot, that is broken links when resources are moved or simply unavailable. Even in the absence of other dependency issues, an obvious requirement is also that any installation key or user accounts requirements must be documented lest otherwise usable software is hobbled.

Installers can be an incredibly useful solution to the problem of missing record references. They provide an easy way to run software. They also can serve as an easy way to redistribute software. One potential caveat is that installers can be derailed if they have an unbundled dependency.

Containers offer another solution. Web based tools are especially vulnerable to disruption because they can immediately go offline if a server is shutdown. Therefore a reasonable effort should be made to enable third parties to deploy web based tools. Creating web based tools and having a downloadable tool are not mutually exclusive and a web based tool could also be made available through the use of containers. This approach can provide a resource for users and create a redistributable container that the provider of the tool can deploy to their own hosting service. However, containerization alone does not give you a sufficient level of introspection. It is a step in the right direction by providing the complete environment required for a tool, but the best containers contain the source code and development environment. A working development environment would allow the highest level of inspection by providing everything necessary to make and test changes to a tool. In order to have plug and play containers it is best if they make use of standard protocols for exchange data and model parameters. In the case of Ecosystem Services Web Services (Lacayo et al., 2021), for example, the data exchange is done as a transparent standard-compliant process. While this is inefficient from a computational perspective it increases resiliency by enabling the different components of the analytical process to be separate and distributed.

4.5.1.4 Problem 4: Permission limited

Reusable software must have a license that allows it to be used for the desired purpose, provides a user guide with clear instructions, and produces intelligible outputs (e.g., values, data formats) in the domain specific context. Increasingly, there is a shift from general public licenses to open licenses that do not limit the location of use, require payment, or have an expiration date. Another important right that a license needs to grant is the right to redistribute the software so that the software can continue to be used and spread without the need of gatekeepers. These open license and redistribution values are not necessarily new but have been formalized in a way that promotes an ethos of FAIRness.

It is highly desirable to use standardized common licenses for several reasons. Developers need to protect themselves legally and also make sure that the rights a user requires are granted. Using custom licenses can result in oversights in legal protections and terms of use. Furthermore, presumably the developers intend for users to read the license, although in reality users often don’t, and using standard licenses with which might be familiar more likely conveys rights and responsibilities. Software dependencies that are bundled with a tool usually have their own licenses and this often must also be provided by the developer. The omission of any of these licenses can result in confusion about the terms of use or even legal liability. Licenses are often provided as “shrink wrap contracts” and “clickwrap agreements” requiring acceptance of the license at the moment it is opened or a website is accessed.

4.5.1.5 Problem 5: Metadata insufficient

As with accessible software, reusable software requires metadata. In order for an ecosystem services assessment tool to be accessible, metadata is needed to assure that the software licenses are accurate and complete and that both inputs to and outputs from the software are annotated to provide complete understanding about values and units. Software license metadata must be clear and indicate license compatibility with all software dependencies. In addition, metadata on software should come from and be contained within inline source code comments, user documentation, a programming guide, API documentation, and broader developer documentation. Both software and data metadata must meet relevant domain community standards and, ideally, be given in a machine readable structured format. Unfortunately, dependencies that would facilitate compliance with and use of metadata standards are not always available and the resources required for compliance can be impractical. In other instances, metadata standards may not support all the features required for software but may be used as a foundation to attain all those features.

4.5.1.6 Problem 6: Documentation limited

In the absence of documentation, even an otherwise perfect tool can be unusable. Good documentation is essential to make full use of software. Documentation is undervalued and often done as an afterthought. It can be written in a free form inside of a word processor, structured text with hyperlinks, or, increasingly, documentation generating frameworks are used with specially formatted source code comments to generate stand alone documentation while maintaining a tight coupling to source code to prevent asynchronicities. There are now platforms such as Read the Docs (https://readthedocs.org/) that host documentation for thousands of projects. Documentation can include a user's guide, a developer’s guide, and more specialized content on the command line interface (CLI) or an application programming interface (API).

4.6 What concrete improvements can be made?

4.6.1 Protocols

Graphical user interfaces (GUIs) lower the cost of adopting a tool but at the same time encourage an analytical process to be performed manually in a way that is not inherently documented, requiring additional resources to create documented reusable workflows. The desire for reproducibility is broadly acknowledged, but the work that is required to both incorporate reproducibility into one's own work and the need for the tools to support it is largely unaddressed. The development of standards for the exchange of data and software has been advanced but the implementation of these standards in well maintained software libraries is fragmented and inconsistent. The motivations around this are not sinister (Lacayo et al., 2021). Rather, the costs in terms of time and money are unappealing for both academics and corporations. Furthermore, in the case of corporations (and individuals) there are real economic interests in keeping people locked into their platforms. To request it to be otherwise requires significant demands from their respective customer bases. This advocates for the development and use of protocols and avoidance of closed platforms.

An emphasis on protocols over platforms addresses locked in costs for data and processing. This has implications beyond the costs of liberating data and workflows. There are also the locked in costs for human resources. The time devoted to learning a user interface or the newest version of a familiar interface could perhaps be more profitably used to understand analytical methods. For example, in GIS one of the most basic operations is geometric intersection. To perform this operation a series of steps is required in any software, principally specifying two data sets for which the common elements will be intersected and kept. In each tool one must learn the specific series of clicks to run the process. However, simply learning what button to click provides no added value. Rather than focusing on executing a particular operation, a deeper understanding can be attained by focusing on the mechanism of the underlying operation.

There have been attempts in the past to shift users towards unified analytical platforms (Börner, 2011; Herr et al., 2006) but in the long run they were not successful. In part, the failure of these efforts can likely be attributed to the difficulties of starting a new platform and to adoption costs. Hopefully, the independent advancement of standards for data exchange workflows, processes, and containerization and a desire for reproducibility will lead to a heterogeneous distributed analytical network using common protocols. The OGC standards for data and their WPS standard for workflows could be the needed protocols for ecosystem services assessment (Giuliani et al., 2012). As it stands, the WPS protocol allows the remote running of the software as a black box, and provides software publishers with a mechanism to assert their intellectual property rights to the most restrictive degrees. We propose extending the WPS standard to require the ability to clone and propagate the underlying process to new systems. This would greatly increase the distributability of a tool and reduce abandonware.

4.6.2 More on Metadata and Design

There is an artificially short lifespan to some of ecosystem services assessment projects and their associated software that is not necessarily the fault of the developers. Multiple factors may unexpectedly shorten software longevity, including the funding mechanism that supports a project. However, there are some principles that, if adhered to, would increase the likelihood of a life past the project end date. First and foremost, making use of an acceptable open source license will allow the project the possibility of taking on a life of its own, independent from its creators. The use of standard software licenses needs to be increased and to propagate the software redistribution should always be allowed. Second and just as important, the steps needed to deploy the software whether locally or as a hosted website should be documented. When possible, containers or virtual machines should be created and offered as turnkey solutions, ideally with developer environments for easy code customization. These principles apply equally to desktop and web based tools. If possible, the latter should also provide a copy or clone mechanism and host installers for any required plugins. Third, make use of existing standards where possible, especially in the area of data exchange and remote execution. While GUIs are generally more user friendly, command line interfaces and application programming interfaces are essential for resilient workflows.

4.7 Resilient Workflows

Resilient workflows will benefit both scientific and policy requirements. On the science side, implementing resiliency principles assists in the creation of original workflows, iterating on those workflows, and sharing workflows. There is a direct line from resilient workflows to reproducibility in science. The difficulty in reproducing one's own work is well acknowledged (Baker, 2016) and in a recent publication on research using mice Kortzfleisch et al. (2022) found that even simultaneous execution of coordinated laboratory protocols did not guarantee reproducibility. Admittedly, the confounding factors in a wet lab are more significant than in a dry lab doing data analysis but the challenge of documenting a workflow in its entirety is also difficult. When focused on the data analysis side of ecosystem services assessments it clearly follows that in the absence of identical methods and tools the ability to reproduce a study is highly unlikely. Lack of access to the methods and tools to verify, continue, and contrast the results of others introduces uncertainty.

On the policy side, uncertainty in the accuracy of ecosystem services assessments begs for solutions that will increase confidence in decisions based on them. Increasingly common requirements for data sharing are raising confidence in scientific results and are also being extended to software. However, this isn't enough. The requirement for sharing should also include sharing a script that emcompasses analytical processes that produce the results. Incorporating established standards into the sharing process would extend their benefits by establishing a clear chain of custody that starts with the data gathering process, continues with selection of analytical tools, and concludes with the results of a workflow. These scripts would then also be detailed documentation capable of producing results on demand. The added value to both scientists and decision makers would justify the extra work and be a large step towards resilient workflows.

Although packaging workflows within software notebooks and tools within containers makes it increasingly easy to be open, workflows can still remain opaque processes and the flow of data and models is not necessarily brightly illuminated. If, however, data exchange standards and analytical process standards were utilized, then there would be clarity in the originating workflow and the ability to repeat and iterate. This sort of transparency is especially useful for reproducibility, comparison, and continuation studies and makes workflows more resilient.

When tools disappear the timeline over which science can mine data with tools to produce information that informs policy is disrupted. Fleeting models and abandonware compromise the analytical environment required for meaningful long term science-policy relationships. Science must be continuously reexamined, refined, and repeated to establish facts (Lombrozo, 2017). Moreover, when the aim is to provide decision support for real world decision processes, actions the evidence suggests will be appropriate and technically feasible must also be implementable and politically acceptable (Dunn & Laing, 2017). Determining political acceptability is often an iterative process, requiring trust and time (Kirchhoff, 2013; Sarkki et al., 2015). When methods and tools disappear the enabling conditions for such ongoing interactions can disappear with them.

There is no question that implementing an analytical process as an automated script is more work. Short term rewards for this additional work may be lacking, but over the long term the effort benefits the creator by making it possible to repeat a process and iterate on it. Scripts will also benefit anyone other than the original provider who wants to reproduce the analytical process. If these scripts for analytical processes were implemented using workflow standards then the disappearance of a tool, resulting in the inability to perform continuation studies, could more easily be remedied through modifying a script to use an available model.

4.8 The Natural Capital Project

The Natural Capital Project was founded in 2006 as a collaboration between Stanford University, the University of Minnesota, The Nature Conservancy, and the World Wildlife Fund. Since its founding the partnership has expanded to include several more prestigious organizations and has collaborated on projects with hundreds of groups (Dolan, 2010; Turner & Daily, 2008). From the outset, the Natural Capital Project invested significant resources in software engineering[2]. It is no surprise then that 3 of the tools identified by Wood et al. (2018), OPAL, RIOS, and InVEST, were created by the Natural Capital Project. Interestingly, each of these tools achieved a different level of FAIRness, accessible, interoperable, and reusable, respectively. As of now, these differences are primarily a result of how the tools are distributed, with OPAL only as code, RIOS as an installer and code, and InVEST in both formats but also actively maintained and updated to the current version of Python, Python 3. It is fantastic that the code is available for all three tools, but as time progresses the tools to compile older Python 2 code become increasingly difficult to obtain.

The FAIRness of InVEST allows users to be independent from any restrictions that the Natural Capital Project might impose willingly, because of internal shifts in priorities, and also unwillingly, because of external changes in funding. The longevity of InVEST software and the longevity of the Natural Capital Project organization have been decoupled and, as a consequence, policy makers can choose to use the InVEST software without adopting any risks from the Natural Capital Project organization. InVEST, as open source software with a permissive license, allows anyone to customize the software and extend or apply it in any way without restrictions.

Despite its many virtues, InVEST has experienced stumbling blocks from changes in technology. Early on, the source code for InVEST was hosted on Google Code (https://code.google.com/p/invest-natcap.invest) but with the impending end of this platform it was migrated in 2015 to Bitbucket (https://bitbucket.org/natcap/invest) without preserving its code history. The current home of InVEST is Github (https://github.com/natcap/invest), which contains the entirety of the code history since the 2015 migration. The detail that InVEST passed through Bitbucket on the way to Github is largely invisible but remains preserved in the Software Heritage archive (https://archive.softwareheritage.org/browse/origin/directory/?origin_url=https://bitbucket.org/natcap/invest). The loss of code history in the migration from Google Code to Bitbucket changes the understanding of and credit for development. If someone

[2] The first author was a GIS analyst and software engineer with the Natural Capital Project from 2011 to 2014.

published results with an old copy of InVEST the advantages of open source software will have been lost in that the underlying code and the science it represents is no longer examinable, rendering early versions of InVEST less FAIR. It appears that in 2021 there was a similar loss of history in access to installers of earlier versions of InVEST when the file host platform changed. All the same, throughout the extensive history of InVEST there have only been minimal losses in spite of significant changes in technology, several funding cycles, and many changes in staff.

InVEST shows careful planning and an adaptable design that bodes well for its longevity. The modular way in which it was developed and the license under which it is released provides flexibility for both deep inspection of the code and easy customization. Each model in InVEST conforms to an API that provides an identical access point for all models with a single parameter of a complex data type. Specifically, each model has a function called Execute that has a parameter Args that consists of the Python dictionary with keys and values that correspond to internal model parameters. This approach allows for easy programmatic access to InVEST so that it can be used in complex workflows. Furthermore, models can be augmented and generalized with international standards (Lacayo et al., 2021) to enable their incorporation into resilient workflows.

4.9 CONCLUSIONS

Acknowledging that while robust science is clearly insufficient by itself for enriched decisions or action (Kirchhoff, 2013; Pielke, 2007; Watson, 2005), we still need to do better than how we are currently performing in this domain.

With regards to ecosystem service assessments, successful SPI-I would support continuation studies, reproducibility studies, and comparative studies, which would enable policy makers to anticipate and monitor the outcomes of practice actions across time and space. Our analysis of 11 ecosystem service assessment tools makes it clear that the current state of the art in ecosystem service assessments does not provide the longevity needed for such studies. Reliance on manual workflows is a key reason for the distance between the promise of ecosystem service assessments as decision support tools and their actual ability to provide the information needed to underpin actions on the SDGs and other biodiversity and sustainable development objectives. The adoption of open source standards would narrow the distance between the promise and the actual practice of ecosystem service assessments as decision support tools and enrich their contributions to the science-policy-implementation interface.

In the immediacy of a need to select a technology it is impossible to make a choice that is certain to result in longevity. However, the use of open source tools presents a greater possibility of longevity. These also have the benefit of the possibility of being put to scientific scrutiny.

Shareable workflows are a best practice for open science and the decision making that it informs. This is best achieved by prioritizing creation of resilient workflows. A manual workflow can never be resilient because it is ephemeral. Resilient workflows are scripted and require elements that endure; FAIRness is a path to achieving that. Each principle of FAIR establishes specific requirements that, when fulfilled, extend the longevity of software. A workflow is a network that consists of both nodes and the links between them and permanence of both is required for resiliency. When a node or a link breaks it must be repairable and that is the very definition of resiliency. The dynamism required for resiliency can only be achieved through protocols, not platforms. Protocols that link to resilient elements should not be locked to them but, rather, accommodate healable losses providing an innate mechanism for a resilient network. The added work this requires yields advantages for the producer and consumer of ecosystem services assessments. The workflow can be rerun to verify results, modified as needed for scenarios, and extended across time and space, allowing for more completeness and reducing uncertainty.

Supplemental Material

F1	F1	F1	F4/A1
Acronym	Long form name	Version number	Official URL
BLOSM	Biomass Location for Optimal Sustainability Model	-	http://blosm.ornl.gov/
CLIMSAVE	Climate Change Integrated Assessment Methodology for Cross-Sectoral Adaptation and Vulnerability in Europe	-	https://www.climsave.eu/climsave/outputs.html
Co$ting Nature	-	3.x	-
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs	3.10.2	https://naturalcapitalproject.stanford.edu/software/invest
LandscapeIMAGES	Landscape Interactive Multi-goal Agricultural Landscape Generation and Evaluation System	-	-
OPAL	Offset Portfolio Analyzer and Locator	1.1.0	https://naturalcapitalproject.stanford.edu/software/opal
RIOS	Resource Investment Optimization System	1.1.16	https://naturalcapitalproject.stanford.edu/software/rios
SERVES	Simple Effective Resource for Valuing Ecosystem servces	-	https://www.eartheconomics.org/serves
SolVES	Social Values for Ecosystem Services	4.1	http://solves.cr.usgs.gov/
UFORE/i-Tree Eco	Urban Forest Effects model	6.1.40	https://www.itreetools.org/eco/

F1	F4/A2	F4/A1	A1
Acronym	Third party URL	Code repository	Access protocol
BLOSM	-	-	HTTP web based visualization
CLIMSAVE	http://82.76.32.108/IAP/	-	HTTP web based
Co$ting Nature	http://www.policysupport.org/costingnature	-	HTTP web based
InVEST	https://pypi.org/project/natcap.invest/	https://github.com/natcap/invest	HTTP installer and source code
LandscapeIMAGES	https://peoplefoodandnature.org/tool/landscapeimages/	-	-
OPAL	https://pypi.org/project/natcap.opal/	https://github.com/natcap/opal	HTTP installer and source code
RIOS	https://pypi.org/project/natcap.rios/	https://github.com/richpsharp/rios-deprecated	HTTP source code
SERVES	-	-	-
SolVES	-	https://code.usgs.gov/solves/solves-4.0	HTTP installer and source code
UFORE/i-Tree Eco	-	-	HTTP installer (registration required) and some web based
Wildlife Habitat Benfits Estimation Tool	http://www.landscope.org/explore/ecosystems/ecosystem_services/defenders_benefit_toolkit/1/	-	-

F1	I4S	I4S	R1.1	R1.1	R1.3	R1.3
Acronym	Compilable	Runable	License	Redistributable	CLI	API
BLOSM	-	-	-	-	-	-
CLIMSAVE	-	-	-	-	-	-
Co$ting Nature	-	-	-	No	-	-
InVEST	Yes	Yes	BSD 3-Clause	Yes	Yes	Yes
LandscapeIMAGES	-	-	-	-	-	-
OPAL	No (Python 2)	No	BSD 3-Clause	Yes	-	-
RIOS	No (Python 2)	No	BSD 3-Clause	Yes	-	-
SERVES	-	-	-	-	-	-
SolVES	Python Compiled Bytecode	Yes	CC0	Yes	Yes (QGIS 3.8.2)	No
UFORE/i-Tree Eco	-	Yes	Public Domain (~CC BY-NC)	Yes	-	-
Wildlife Habitat Benfits Estimation Tool	-	-	-	-		-

5. EXTENDING THE BENEFITS OF ECOSYSTEM SERVICES WEB SERVICES (ESWS) TO EDUCATION

Paper in development

Target Journal: *Environmental Modelling & Software*

(https://www.sciencedirect.com/journal/environmental-modelling-and-software)

5.1 Introduction

Threats to human wellbeing from loss of ecosystem services are a call to action to better manage our relationship with nature (IPBES, 2022). Aspirations for a more sustainable and equitable future are integrated into the United Nations sustainable development goals (SDGs). The ecosystem services approach is an effective way of framing nature’s benefits to people and these benefits have been identified as being critical to may SDGs (Wood et al., 2018; see, also, Chapter 4). If the SDGs are to be achieved and people internalize the importance of ecosystem services, the political changes needed will require that at least a vocal minority of the public understand these topics at a general level (Chenoweth & Stephan, 2012). It is prudent and pertinent, then, to educate people on ecosystem services and train them to carry out ecosystem services assessments.

The question is, then, how to teach about ecosystem services and, in particular, build capacity for conducting ecosystem services assessments. Among the challenges to building a broader base of expertise is that technical requirements can present a barrier to uptake and frustrate potential learners. One approach to this problem can be to lower the uptake costs by increasing the accessibility and decreasing the computer resources required for learning by moving ecosystem services tools to the cloud. Likewise, the scale of the learning that will be required and the resources available to provide education on ecosystem services suggest that massive open online courses (MOOCs) can be an efficient and effective medium through which to convey this critical knowledge. In this chapter, the University of Geneva MOOC, “Ecosystem Services: a Method for Sustainable Development”, is discussed and potential expansions to its game-based learning and GIS tutorial are proposed. The method discussed is based on using international standards for geographic data and processing that are widely available and can be freely used in a variety of traditional or online courses.

5.2 Background

In this background, we will cover ecosystem services as the framework through which we understand nature’s benefits to humans. We continue with a discussion of the strengths and weaknesses of MOOCs and serious games. We conclude with a discussion of Software as a Service and how it may bring all these elements together.

5.2.1 Ecosystem services

Ecosystem functions such as the retention of water, soil, and nutrients give rise to ecosystem services (ES) including water supply, erosion control, and nutrient cycling that are critical for human well-being (Costanza et al., 1997; Daily et al., 2009; Ehrlich & Mooney, 1983). This concept has been adopted widely as a means of explicitly linking changes in the environment and benefits to humans in spatial planning, biodiversity conservation, and in the broader realm of sustainability science. The ES framework supports contextualization and comparison of gains and losses that could result from action and inaction on different environmental policies and practices. Such analyses are increasingly demanded as global consumption increases and human populations grow, even as environmental degradation and climate change cause mounting uncertainty about capacity to meet these demands equitably and sustainably. This is both a scientific problem and a political problem, requiring suitable science-policy interfaces to translate findings into action (see Chapter 4).

Capacity-building is a deliberate, voluntary process to expand on knowledge (Franco & Tracey, 2019). Building local capacity is essential because it fosters a sense of ownership and promotes long-term success by engaging local stakeholders (Ruckelshaus et al., 2015). In many localities with the most threatened ecosystems, the resources needed to increase ecosystem service assessment capacity is elusive. Therefore, the importance of building local capacity, as also indicated in previous studies (Saarikoski et al., 2018), co-located with urgent environmental issues make building capacity for ecosystem service assessments especially important.

5.2.2 Ecosystem Services Web Services

Ecosystem Service Web Service (ESWS; see Chapter 3) is a proof of concept for transforming desktop based geoscience software into a cloud based software as a service (SaaS) architecture using OGC compliant standards and consists of both a web browser based user interface and a Python library of functions (Lacayo et al., 2021). Functionally, this is achieved through a custom built middleware that handles error tolerant input and output as well as model running. The Integrated Valuation of

Ecosystem Services and Tradeoffs (InVEST) annual water yield model was transformed with ESWS into cloud based software by connecting each data input, model parameter, and data output for the water yield model to relevant OGC standards. It should be noted that, in effect ESWS speaks a language that is widely available in this context but would require more development to achieve the same compatibility with other models. The transformation from desktop software to cloud based software means that with the use of a simple dashboard interface, remote data transfers can be initiated by a user so that a remote process downloads data to the water yield model, runs the model with the user specified parameters, and stores the results on a remote server, all using OGC standards. The significance of this is that it changes both the access mechanism and computer resource consumption, shifting the deployment architecture of desktop based software into cloud based, a form that is both more flexible and compatible with online learning.

5.2.3 MOOCs

There is a long history of putting course material online and this has been extended into massive open online courses (MOOCs). The scalability of MOOCs meets educational demands efficiently in an ever more budget conscious climate. This drive towards online learning greatly increased in the first two years of the COVID-19 pandemic. The pandemic also highlighted a need for the sustainable management of resources in light of massive increases in medical waste and threats from other zoonotic diseases. MOOCs are believed by the students to offer more learning with less effort, but it is the perceived ease of use and perceived usefulness that are key for successful acceptance of and intention to use MOOCs. This intention is further amplified by computer self-efficacy, that is the confidence one has capabilities to successfully complete a task, and perceived convenience based on location, time of day and duration, required tools, financial costs, and form of delivery. (Al-Adwan, 2020)

MOOCs have been touted as offering universal access to education for anyone with an internet connection but have not yet fulfilled this promise. Furthermore, evaluations of MOOCs are most commonly based on users' self-assessments and rarely on quantified objective gains. Blum et al. (2020) performed a metaanalysis of 17 studies and concluded that there have been gains in areas that include knowledge, self-confidence, and enthusiasm, but the overall benefits to learners are not clear. Satisfaction is not the same as efficacy, but for MOOCs this is not well studied.

Nevertheless, the Coursera catalog includes numerous MOOCs that address sustainability and/or ecosystem services, developed by universities in Africa, Europe, and North America (https://www.coursera.org/browse/physical-science-and-engineering/environmental-science-and-sustainability). These include:

- Ecosystem Services: a Method for Sustainable Development (University of Geneva)
- Climate change and Indigenous People and local communities (Universitat Autònoma de Barcelona)
- Climate Change Mitigation in Developing Countries (University of Cape Town)
- Environmental Management & Ethics (Technical University of Denmark)
- Global Environmental Management (Technical University of Denmark)
- How Do We Manage Climate Change? (University of Colorado, Boulder)
- Planning with Climate Change in Mind (University of Colorado, Boulder)
- The Age of Sustainable Development (Columbia University)
- The Sustainability Imperative (University of Colorado, Boulder)
- Water Resources Management and Policy (University of Geneva)
- What is Climate Change? (University of Colorado, Boulder)

Collectively these courses are estimated to take approximately 148 hours to complete, clearly a substantial offering. MOOCs can benefit from gamification, but there are important design considerations, namely that games like MOOCs must carefully address engagement, performance, and motivation and while carefully choosing each game element so as not to distract from the underlying lesson (Antonaci et al., 2019).

5.2.4 Serious games

The interdisciplinary nature of sustainability issues and the multiple scales at which humans make management decisions lends an inherent complexity to learning about sustainability, but simulations and games have been shown capable of simultaneously achieving multiple learning goals (Diniz dos Santos et al., 2019; National Research Council, 2011; Stanitsas et al., 2019). These games, designed for more than solely entertainment purposes, are called serious games (Ouariachi et al., 2019).

Serious games have been shown to be highly useful and there is concrete potential to integrate them into ecosystem services education (Costanza et al., 2014). Teaching the natural capital and valuation concepts through a serious game holds great promise because educational games already incorporate in their design learning concepts, inspiring motivation, accepted educational strategies, active participation, teamwork, and competition (Verutes & Rosenthal, 2014).

The literature about serious games is dominated by commentaries (55%) and empirical studies remain a minority (33%) and even then do not use an experimental design but rather rely on descriptive methods (Hallinger et al., 2020). Exploring the efficacy of serious games in sustainability will benefit from quantifying the empirical effects of performance, motivation, engagement, attitude towards gamification, collaboration, and social awareness (Antonaci et al., 2019). Nevertheless, game-based learning in some contexts has been shown to provide knowledge acquisition at a rate nearly the same as traditional teaching, while providing an experience much more motivating and fun (López-Fernández et al., 2021). Furthermore, game-based learning has also been effective for teaching sustainable development with unrelated technical skills (Swacha et al., 2021). Therefore, presumably the synergy of teaching sustainability with related technical skills will be even more effective, as in our case.

5.2.5 Software as a Service

Software as a Service can be understood as software on demand. That is to say that the software itself is not installed by the user but, rather, is immediately available for use with core functionality fulfilled by a remote process. This architecture requires a client side interface to server side functionality. The client side is often considered a thin client, in that very little beyond input and output operations are happening, while the heavy lifting is done on the server side. This architecture has become ubiquitous and is embodied by the email and chat websites that the majority of the world uses. This form of delivery is appealing to both providers and users because it allows for minimizing per user costs, it can accommodate heterogeneous hardware while maintaining control over the user experience, access can be easily controlled, and it can leverage other technologies such as cloud computing and storage to the benefit of functionality.

5.3 Teaching ecosystem services through MOOCs and serious games

In the interest of exploring the use of serious games in teaching about ecosystem services, the Natural Capital Project debuted the game "Best Coast Belize" in 2011 as an interactive exercise during in person training to explore the tradeoffs in marine spatial planning with the purpose of introducing a diverse audience including students, researchers, decision makers, and NGO practitioners to concepts of nature's benefits to people. Through an interactive design process the game evolved into two games collectively called "Tradeoff!", with one focusing on coastal and marine ecosystem services, and the other focusing on terrestrial and freshwater ecosystem services to increase audience relevance. As of 2014, more than 1,000 people had played the games, which were generally well received especially in educational settings. Josh Goldstein, director of the Bridge Collaborative at The Nature Conservancy, and former assistant professor at Colorado State University, described Trade-off! as a "smash hit!" with undergraduate students (Verutes & Rosenthal, 2014, p. 7). The reach and geographic breadth of the Natural Capital Project trainings is impressive, but remains constrained by costs and scalability.

In 2017, to explore the use of MOOCs in teaching about ecosystem services, the University of Geneva offered the "Ecosystem Services: a Method for Sustainable Development" MOOC on the Coursera platform. The course, which is estimated to take 18 hours to complete, consists of six modules and begins with an introduction that includes playing a digital version of Tradeoff! : Agriculture edition! (https://esgame.unige.ch/) and concludes with a GIS tutorial. In between, historical contexts, case studies, interviews with professors, and discussions include the topics of valuation, ethics, tools, and governance. As of 2022, more than 32,000 people have enrolled in the MOOC, with an average course rating of 4.8 stars out of 5 and 98% favorable rating for the content. The average annual exposure rate of the MOOC is approximately 20 times higher than that of the in person trainings offered by the Natural Capital Project. This reflects a variety of differences but is most probably higher due to lower costs and ease of access for participants. Indeed, analytics for the serious game, which is free and, while unadvertised, can be accessed outside of the MOOC, show access by more than 12,000 users in 175 countries and territories. Aggregating the users by subcontinental regions (figure 1) or by cities (figure 2) shows high geographic dispersal and highlights broad interest across the globe, especially in places where in person ecosystem services teaching is unlikely to be available.

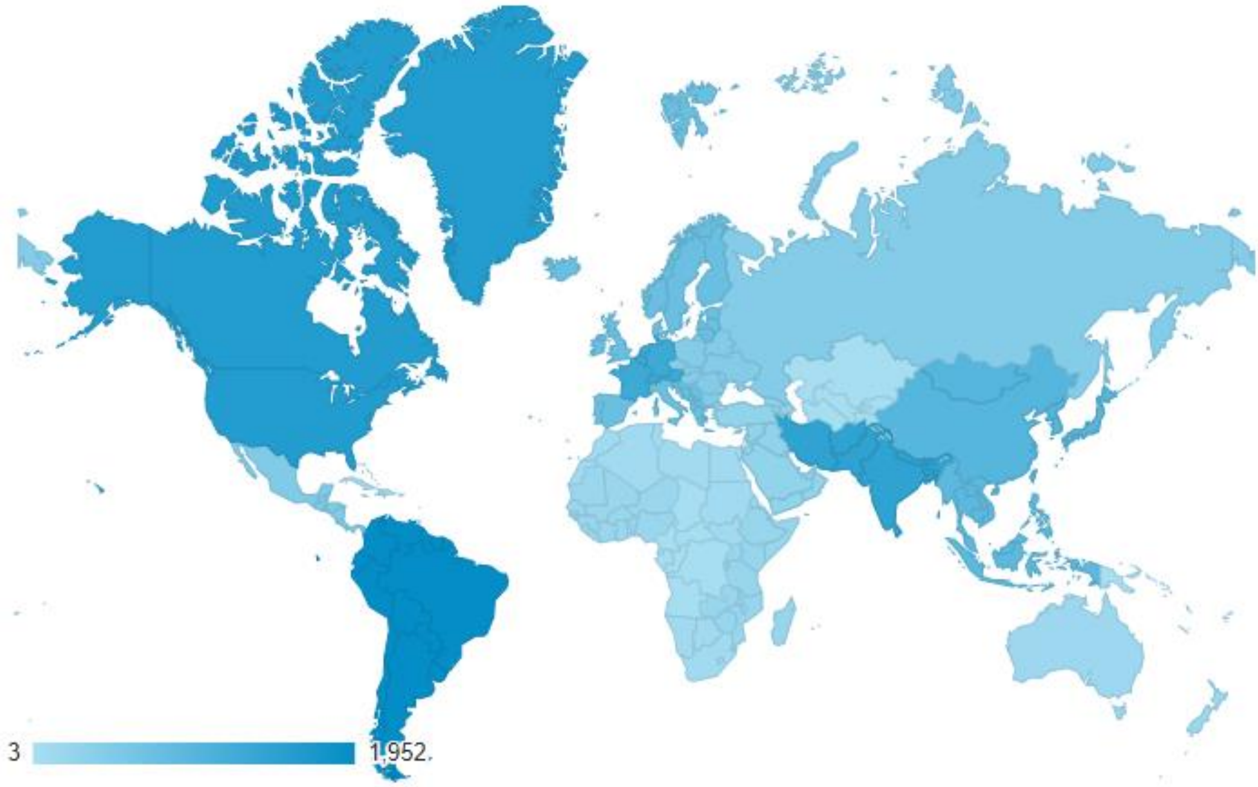

Figure 5.1 Map of game visitors aggregated into 23 subcontinent regions.

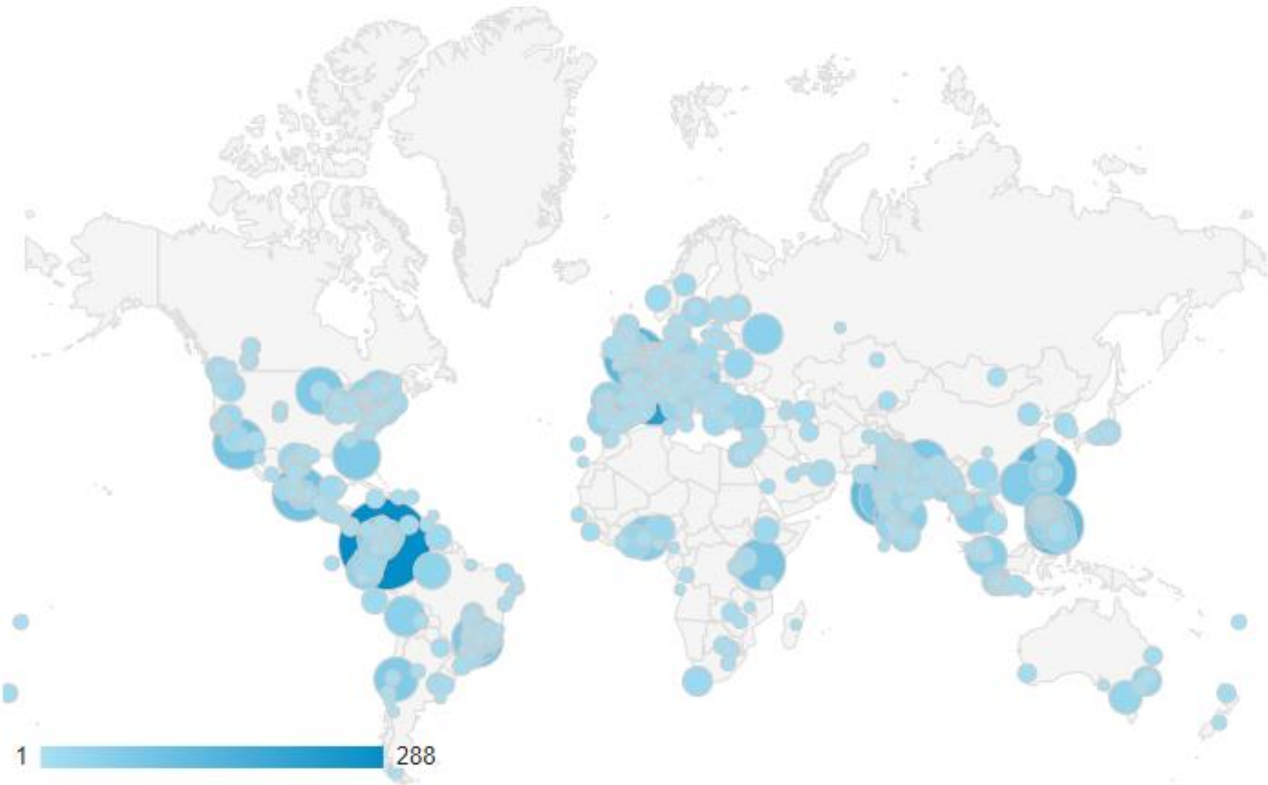

Figure 5.2 Map of game visitors aggregated by 2,000+ cities.

The appeal of the Trade-off!: Agriculture Edition game is the simple way of exploring the trade-offs between ecosystem services and facilitating discussions. The ES game is played in two rounds where users explore tradeoffs between agriculture (figure 3, left) and ranching services while losing habitat quality, water quality, (figure 3, right) carbon, and hunting and foraging services. In the first round, the objective is to maximize revenue by creating four corn farms and four cattle ranches (figure 4, top). In round 2, the objective is to maximize the net score that takes into account losses of ecosystem services (figure 4, bottom). This is meant to convey the effect that someone can have on ecosystem services and how changing decisions can have different impacts on people and nature.

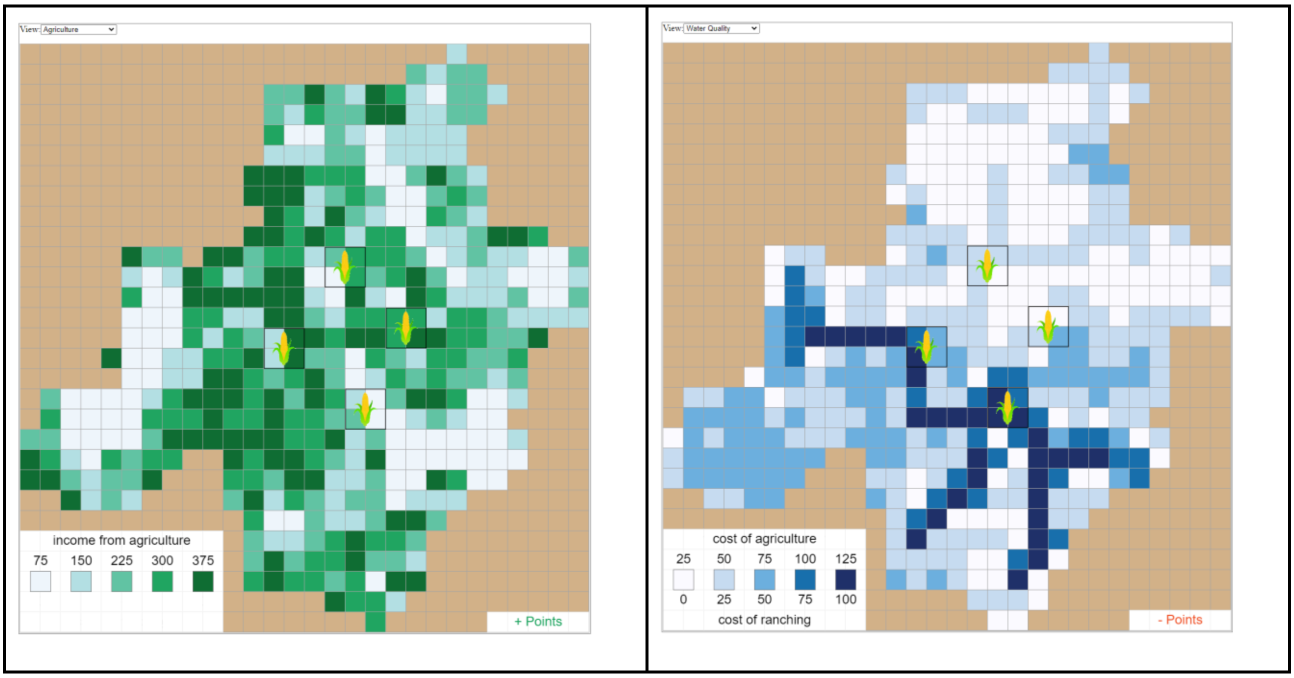

Figure 5.3 Gains from agricultural map (left) and losses from water quality (right).

Round 1 Score								
				Agriculture		Ranching		
				3750	+	2900	=	6650
Habitat Quality		Carbon Storage		Hunting and Foraging		Water Quality		
-2025	+	-1350	+	-1325	+	-1025	=	-5725
						Net	=	925
Round 2 Score								
				Agriculture		Ranching		
				3750	+	2250	=	6000
Habitat Quality		Carbon Storage		Hunting and Foraging		Water Quality		
-2575	+	-1425	+	-1125	+	-1325	=	-6450
						Net	=	-450

Figure 5.4 Scoresheet showing score from round 1 (top), made without knowing environmental losses, and score from round 2 (bottom), made while knowing environmental losses.

Module 6 of the MOOC is a GIS tutorial for the InVEST water yield model under climate change scenarios using globally available data sets and QGIS. It is divided into five lessons: data gathering, preprocessing, running the InVEST water yield model, preparing a climate change scenario, and visualizing the results in a map. The data gathering lesson directs the users to six websites that have global data for each of the required parameters of the InVEST water yield model. The preprocessing lesson details the step-by-step process to create a custom area of interest for the focus of the analysis and how to use it to remove any unneeded data. The next lesson shows how to run the InVEST water yield model with the prepared data. The climate change scenario lesson directs participants to climate change scenarios from the IPCC and instructs them how to run the water yield model with the future scenario. The model is concluded with step-by-step instructions on how to visualize the results in a map. These lessons provide an introduction to using QGIS with InVEST to calculate water yield under climate change scenarios.

The game and GIS tutorial could both be improved in several ways. The game would benefit from group play with chat capabilities, local offsets within farms or ranches, and estimated real world values for specific locations. The last point is one focus of this article and is addressed in the next section. The GIS tutorial is now five years old and contains several broken links for data and was made for QGIS 2.16.1 Nodebo is one major version and 15 minor versions out of date encompassing significant changes rendering some of the tutorial instructions nonfunctioning. In the next section we will focus on how to separate GIS functions from their QGIS forms.

5.4 Teaching with ESWS

There is educational value to ESWS. The features of ESWS that provide benefits in a scientific analytical environment (see Chapter 3) also have advantages in an educational context. The modular workflow that improves reproducibility, iterations, and goal seeking parameter optimization in the scientific context allows students to document, repeat, and refine their work, both demonstrating and improving their skills. ESWS capacities for facilitating scientific collaboration can also be used in the education context to facilitate group projects, supervision, and enable evaluation. ESWS creates playable workflows and in an educational context this allows experimentation and the development of critical thinking through iterations and refinements of the workflow. In addition to facilitating understanding of how individual models work, ESWS provides the students with the tools needed to understand how one model can provide results for another model and work in concert to answer bigger questions.

Specifically, ESWS can enable the MOOC game to have estimates for real world values in a user specified location. This could help make the game more interesting and relatable for students. This could be achieved in two ways. First, by using the input/output capabilities of ESWS to read precalculated ecosystem services layers for real world locations. Fortunately the game is implemented in JavaScript, and this would actually only require a small modification of the ES game to cache data from OGC compliant sources. Second, for more advanced students using the full capabilities of ESWS to run workflows whose outputs could become custom layers for the game. These layers could then be published using ESWS and utilizing the first solution incorporated into the game. In addition to improvements to the game, improvements to the tutorial could also be made.

The first technical challenge that students may experience when using the MOOC GIS tutorial is that their computers may not support the tutorial's version of QGIS if, in fact, at this point they can even obtain it as it is rather dated. All versions of QGIS have computer operating system and resource requirements that may not be compatible with the student's computer. This could be the first place that ESWS would help, by serving as a front end to a server based version of QGIS. ESWS as an educational tool would minimize hardware and set up demands on students.

Using ESWS would allow students to learn GIS independent of any user interface that might change over time. In fact any GIS for which there is a WPS interface could be used with ESWS. This means that geographic concepts like a buffer could be taught agnostically with respect to the GIS platform that would actually do the computation. For more advanced students, this would be an opportunity to introduce the concepts of APIs and basic programming with ESWS.

With more advanced students ESWS programming can be used to teach the logic of a workflow including sequential dependency and iterations. In ESWS, workflows are conceptualized as having nodes that are linked through inputs and outputs with dependency determining when a node has all the inputs to run. Inputs are consumed and outputs are generated. Inputs that cannot be accessed, either because of a network error or because the data does not yet exist, are repeatedly tried for a user specified number of times at a user specified interval before failing. Inputs that are accessible are immediately cached and when all the inputs for a node are available, then the node will run and produce outputs. These outputs can serve as inputs to a different node. In this way, when outputs from one node are fed as inputs to another node the error tolerance of the input/output operations is leveraged to create workflows. The error tolerance mechanism functions as a way to synchronize nodes allowing nodes with all their inputs available to run and nodes with unavailable inputs to wait and run again in the hope that an unavailable input becomes available as a result of either an improvement in network access or the creation of output from a node.

ESWS would allow students to focus on analytical development and not on learning a one particular tool or model. The flexibility of the OGC standards allows for the possibility to teach a simple model for water yield and later build on that foundation to teach a more complex water yield model. ESWS allows students to focus on the workflow. Learning to use ESWS is a portable skill because OGC standards are not locked to are open standards and implemented by many platforms.

ESWS runs models by generating server side scripts that feed cached inputs into the model and publish outputs from the model with OGC compliant standards. This requires knowing input requirements and any resulting outputs prior to run time so that a static template can be created for each model. In the case where the number of inputs or outputs can vary based on the specific parameters this is not well suited to OGC standards, but can be achieved through a network/web accessible watch folder. At present, ESWS acts as glue to create OGC web service workflows that can be created through a basic web interface or Python scripting, but ideally would be built upon to create a visual programming environment similar to Node-RED (figure 5).

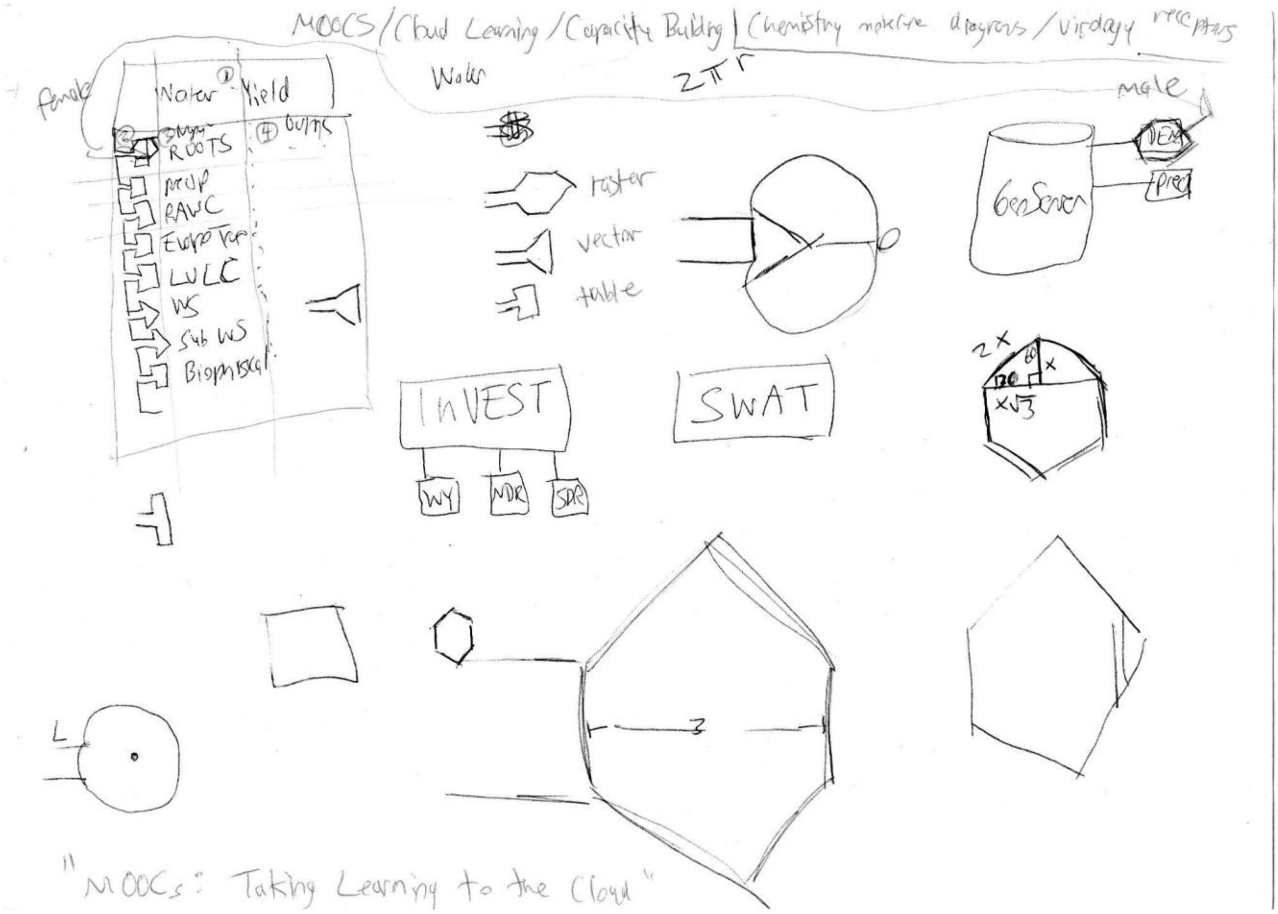

Figure 5.5 Example of graphical programming elements of an ecosystem service assessment.

There are several non-technical benefits that can help with psychosocial aspects of teaching. The ability to work with models from a top down approach and produce individualized results can help to reduce frustration and attrition rates. The ability to use previously desktop based software, such as InVEST, through a thin client web interface reduces hardware requirements improving social equity through the reduction of the digital divide. This ability to use complex ecosystem services assessment tools remotely also means that students are not required to be physically present in a computer lab, which can be attractive by providing flexibility in where the software can be used and, in the case of pandemics, also protecting health through options for isolation.

5.5 Conclusions

There is a profound and urgent need to manage natural resources better and the ecosystem services concept provides a framework for understanding how gains and losses can have a direct impact on human wellbeing. This understanding needs to shift human behavior at a large scale but this will require capacity building through the education of students so that our future scientists and decision makers understand the consequences of their actions better. The scale of the resources allocated to accomplishing this critical goal are lacking and therefore a practical approach is the creation of ecosystem services MOOCs and serious games.

MOOCs and serious games are generally very well received and have been shown to be effective in some ways but there is a real need for further empirical studies, especially using experimental designs. Static lessons lacking dynamic and interactive components are useful but to really engage students making the materials personally relatable and relevant is important.

One way to accomplish this is to allow the students to choose the location of focus both in MOOCs and serious games. This need for customization and relevancy while being technically accessible to students calls for a new approach to GIS training. The ecosystem service web service (ESWS), both as a user interface and Python library, provides a possible solution with several benefits. In the specific area of MOOCs and serious games ESWS can facilitate the location customization and also more complex capabilities. ESWS disentangles GIS skills from GIS interfaces and allows students to focus on analytical reasoning and critical thinking. This pathway can begin with understanding workflows and expand into learning about APIs and basic programming. Ideally, ESWS would be further developed to include a visual programming environment, but regardless it can enable mobility and flexibility in a time when the digital divide persists and attending a class in person can be dangerous for your health. The hope is that by making lessons more personal and engaging will reduce attrition rates, build our ecosystem services capacities, and help provide the much needed changes to manage our world better.

6. CONCLUSIONS

Creation and testing of a webservice based approach to achieve interoperability for production and reproduction of ecosystem service assessments is the original contribution of the work described in this thesis. I have addressed the problem of technical challenges to the creation and reproduction of ecosystem service assessments using existing data by answering six research questions. In this chapter, I revisit each of these questions, offering conclusions on how the answers derived from the literature and the development and application of the Ecosystem Service Web Service (ESWS) contribute to answering the research problem at the heart of this work. I conclude by offering perspectives on how the ESWS solves some key technical obstacles that adversely affect ecosystem service assessment.

6.1 Importance of ecosystem service assessments

While there is no singular definition of ecosystem services (Fisher et al. 2009), it is broadly understood as a conceptual framework for understanding the benefits humans derive or receive from ecosystems (MEA, 2005). Despite, or perhaps because of the multitude of ways in which the ecosystem services concept has been applied, it has underpinned tremendous empirical and theoretical scientific advances for more than two decades (Costanza et al., 2017). It remains a widely used and highly productive framework for conducting policy relevant science.

Ecosystem service assessments operationalize the ecosystem service concept. Ecosystem service assessments are in widespread use to evaluate environmental challenges facing humanity from risks of local flooding (Li et al., 2018) to pressures on global tourism destinations (S. A. Wood et al., 2013). Ecosystem service assessments are typically complex. It is not uncommon for them to evaluate multiple ecosystem services, use a variety of data sources and types, and employ multiple methods (Dunford et al., 2018). Frequently, ecosystem service assessments also are conducted by multidisciplinary teams. This diversity in ecosystem service methods and tools is a strength, for example allowing modeling of the interdependent dynamics of a study area and evaluation of the interplay between oppositional or mutually reinforcing ecosystem service benefits. Diversity is also a source of challenges.

Many ecosystem service assessments make use of existing data. An abundance of existing data can and does provide information at spatial scales from the local to the global, and temporal scales from single points in time to long term observations. Among the chief advantages of using existing data is its potential availability. However, in actual practice the technical challenges to acquire and use existing data often are extensive and occasionally insurmountable when they must be accomplished manually. Gathering data from disbursed sources and harmonizing them frequently takes months and occasionally proves impossible. Calibrating parameters and fine-tuning algorithms to accurately represent the phenomena of interest can be arduous, especially where software is designed in a way that is not optimal for the task. These challenges are compounded when different data types are integrated, as they typically are in ecosystem service assessments.

Among the technical challenges to be overcome in the creation of ecosystem service assessments that use existing data are identification of the services for which there are available data, obtaining location and context information for the data, securing access to the data, selecting or developing software, and integrating these elements in a thorough and comprehensive way to obtain the results needed for a detailed analysis.

6.2 Technical approaches to better ecosystem service assessments

The ESWS approach offers a solution to many of the technical challenges in the execution of ecosystem service assessments. By taking an intentional approach to interoperability, ESWS streamlines the process required to create, iterate, and disseminate an assessment. Adopting OWS allows ESWS to readily integrate tabular, raster, and vector geographic data for geoprocessing into complex, documented, interoperable workflows. This readily allows ESWS to combine existing data and software in novel and timely ways. Collectively, these features instill resilience and agility into ESWS workflows since all components are remote.

ESWS improves ecosystem service assessments in three ways: (i) the creation of new OWS resources (i.e., elements); (ii) facilitated access to first party and third party OWS resources (i.e., links); and (iii) workflow creation and management using OWS resources (i.e., elements with links). These three features yield a host of advantages (Table 6.1).

Table 6.1 Advantages of the ESWS approach conveyed through (i) elements, (ii) links, and (iii) elements with links.

Elements (i)	Links (ii)	Elements with Links (iii)
1. Modularity	7. Integration	13. Workflow
2. Access control	8. Future proof*	14. Sharing
3. Provenance	9. Fault tolerance	15. Collaboration
4. Automation	10. Transparency	16. Standardization
5. Scalability	11. Chain of custody	
6. Interoperability	12. Compliance	

Table 6.2 Advantages to science of the ESWS approach conveyed through (i) elements, (ii) links, and (iii) elements with links.

Elements (i)	Links (ii)	Elements with Links (iii)
1. Customization	7. Flexibility	13. Reusability
2. Exclusivity	8. Uptake costs	14. Validation
3. Assurance	9. Reliability	15. Collaboration
4. Efficiency	10. Clarity	16. Defensibility
5. Efficiency	11. Confidence	
6. Flexibility	12. Obligations	

Table 6.3 Advantages to policy of the ESWS approach conveyed through (i) elements, (ii) links, and (iii) elements with links.

Elements (i)	Links (ii)	Elements with Links (iii)
1. Scenarios	7. Preparation	13. Documentation
2. Discussion	8. Reusability	14. Openness
3. Robustness	9. Reliability	15. Collaboration
4. Scenarios	10. Clarity	16. Consensus
5. Scenarios	11. Sources	
6. Scenarios	12. Obligations	

Table 6.4 Advantages to education of the ESWS approach conveyed through (i) elements, (ii) links, and (iii) elements with links.

Elements (i)	Links (ii)	Elements with Links (iii)
1. Tinkering	7. Flexibility	13. Clarity
2. Grading	8. Skills	14. Grading
3. Citations	9. Troubleshooting	15. Group project
4. Abstraction	10. Clarity	16. Defensibility
5. Equity	11. Reasoning	
6. Flexibility	12. Grading	

6.2.1 Elements

In ESWS, elements are OWS resources. These resources are created by encapsulating tabular, raster, and vector data, as well as geoprocesses in their corresponding standard. This conveys a host of advantages including modularity, access control, provenance, automation, scalability, and interoperability. This section describes the advantages conveyed by ESWS elements.

Modularity is the ability to choose a scale to define as indivisible or atomic. Modularity in the ESWS means that every component, at every step of an assessment, can be considered an interchangeable part. This provides a mechanism by which each component can be changed by swapping in a new compatible data set or geoprocess element. At different scales of modularity, this could mean the new component is composed of loops to batch run model calibration, custom alteration of algorithms, or automatic data selection using semantic information.

Access control is the ability to finely set permissions for reading, writing, and execution of elements. Granular access control is achieved by leveraging the underlying web technologies used by ESWS. Such control enables a spectrum of openness from being completely opaque, with nothing shared, to completely transparent, with everything available under an open license via permanent URLs. Access control becomes a matter of choice and provides mechanisms to assert attribution requirements and enforce use restrictions. Furthermore, the separation between user, data, and software enables the possibility of using restricted data in a model, providing results derived from the data even where access to the original data would not be permitted or practical.

Provenance is knowledge of and the context for understanding metadata. Provenance is at the core of the underlying mechanisms for ESWS. Every element, whether input, process, or output, has an OWS address within ESWS, accompanied by metadata. The use of OWS addresses within ESWS makes it possible for an ecosystem service assessment to change any element while keeping track of information context and sources.

Automation is the ability to filter or do unit conversions or geographic transformations based on data or metadata. Automations can filter and normalize based on geoprocessing metadata. For example, data types or even semantic information imbedded in a geoprocess could be matched to the corresponding metadata of an ESWS elements to ease the manual selection of data with filters or automatically select the most likely candidate data source (Nativi, Craglia, et al., 2013).

Scalability is the ability to increase computational capacity to meet an increased demand as a problem gets bigger. In ESWS, scalability is achieved through the underlying OWS web technologies. Data is stored and processed remotely and options for redundancies to ensure protection against failures and distribution to improve performance can be enabled. These redundancies can mean that a user of the ESWS does not have to be concerned with backing up their data or the availability of resources for running hundreds of models because server management can be leveraged to address these issues. For example, GeoServer's plugin to extend WPS with the Hazelcast computer cluster software can be used to distribute and coordinate model runs.

Interoperability is the ability for elements to be used with each other. In ESWS, the OWS encapsulation of each element gives them a form and function that establishes interoperability with other elements. This interoperability provides the required starting conditions for linking to data sets and methods from a variety of sources.

6.2.2 Links

In ESWS, links are references to elements. Links contain the information needed to manage the tracking of elements within ESWS and serve as the means for reaching an element and accessing any of its data, metadata, or functionality as described in 6.2.1. The separation between elements and links is made to remain OWS compliant while gaining additional functionality. This functionality includes integration, future proofing, fault tolerance, transparency, chain of custody, and ease of compliance. Using links in ESWS makes it possible to gather resources in a unified way, enabling the integration of heterogeneous sources, such as those from multiple data providers or ecosystem service assessment tools.

In adopting OWS as the protocol of choice, ESWS embraces a well established mechanism for openly integrating new geospatial data and processing components. With perhaps the unlikely exception of a new data model being incompatible with the raster or vector concepts, the way in which ESWS handles data can largely be considered future proof. Users can dynamically meet their needs on an ad hoc basis through the standard API of OWS, greatly simplifying implementation. Any third-party software that is compliant with the same API standards can readily be integrated in an implementation agnostic way.

Fault tolerance in the ESWS is achieved using a customizable number of retries and delay intervals between retries to reach a resource and cache it when possible. When a data or process resource is unreachable, including when it is still being created, the execution pauses the running of each job until all its inputs are available. This same mechanism can be used to put an analysis on standby for months or years, waiting for data that will be available in the future, provided it will have a known address. In this way, you can set up resilient, reactive workflows that will manage themselves.

Transparency with the ESWS is easily achievable because all work has to be done using documented links, with all the components of the analysis stored in the cloud, whether locally simulated or actual, making transparency simply a matter of adding user permissions for anyone from a relevant authority to the public, as desired. The nature of these links as modular, interoperable components with explicit provenance establishes a chain of custody for any analysis. Furthermore, because of granular access control and the transparency inherent to ESWS, any level of requirement for or prohibition of disclosure can be accommodated to meet compliance requirements from institutional or funder policies for preservation or openness.

6.2.3 Elements with Links

The ESWS is an end-to-end solution for integrating data and method resources from diverse OWS sources. These resources are queried, indexed, and bookmarked to allow for an unprecedented level of seamless integration for novel and timely analysis. The ability to readily integrate distributed data and methods leverages the strengths of existing computer and human resources more efficiently. The value of ESWS goes beyond conglomerating software through a common API and user interface for computer and human resource efficiency. It facilitates the creation of self-documenting workflows that can seamlessly share and publish results while maintaining user control over access. The creation of new OWS resources in combination with the ability to link all OWS resources imparts a distinct advantage in the creation of workflows, sharing individual and collections of resources, collaboration, and ultimately consensus building through the inspection and, where possible, standardization of analysis. Combining different ecosystem service assessment methods within and between toolsets can lead to a more complete analysis and allow for different scenarios to be more fully compared and contrasted.

The ESWS removes the division between creating a workflow and documenting the process by simultaneously producing both. The workflow for the analysis describes how all the inputs, processes, and outputs are connected, which simultaneously functions both as what produces results and the documentation to reproduce the work. In effect, it could be viewed as ESWS requiring a user to produce documentation for an analysis that automatically generates a workflow.

Furthermore, because OWS is used to connect every step of the workflow, then any third-party data via TJS, WCS, and WFS, and third-party software via WPS can also be integrated. This could mean, for example, that an update to a land use land cover map could be simply swapped into an existing workflow by changing a WCS address or a new version of a software could be used by changing a WPS address, either of which would yield a new assessment. In combination with the fault tolerance mechanism of ESWS, a workflow could be reused immediately as a template for a future analysis waiting on an update to, for example, the same land use land cover map, reducing task switching costs and potential errors from data entry. With appropriately synchronized values for the number of retries and retry delay, a workflow could produce results shortly after the required future data sets are published.

Sharing a workflow is then more easily understood as sharing documentation. Just as with sharing any other kind of documentation, a user must simply be granted appropriate access permissions. The user permissions can cover the range from being able to completely inspect and copy an element to an external location or only being able to use the element in the workflow without inspecting it. In the case of collaboration, a user would be granted write and execution permissions, while other users would be granted different permissions. The level of openness for sharing input data, preprocessing, processing methods for analysis, computational environment, and results is all under the same granular control of the author.

The ease with which ESWS allows for sharing and collaborating on workflows should allow for the dissection, discussion, and development of workflows in an unprecedented way, facilitating creation, iteration, and curation. This can, in turn, enable the ability to standardize and formalize analyses that to date are performed manually on a case-by-case basis. The standardization of methods can simplify complex assessments and promote open science.

6.3 Contributions to science for ecosystem service assessments

ESWS elements are the indivisible atomic components, which can have an associated set of inter-element links that collectively form a workflow. The elements have several features that allow them to assist scientists to conduct ecosystem service assessments more easily. Element modularity forms the basis of interchangeable parts that can be customized and exchanged as needed. Access control provides security and exclusivity when needed for confidentiality or development. Provenance is one of the most important features of ESWS, in that everything must have a source origin and associated metadata, and this conveys assurance in knowing where something comes from. Automation, in this case, refers to the ability to automatically process elements based on data type or other metadata, increasing efficiency by not having the requirement of necessarily doing this manually. For example, if a particular data type is needed for a parameter the default selectable parameter values will match that data type. Scalability is also about efficiency in that the use of an element is non-blocking, allowing for parallel use and distribution as needed. Interoperability in elements provides a flexibility so that they can be used with other elements.

In the ecosystem service assessment context, modularity is especially useful because each ecosystem service, locality, and scale can have specific features that are unique, making customization important. Access control is widely understood to be important, but especially for assessments when done in sensitive areas with competing goals. It can also protect scientific independence and confidentiality, which can sometimes be necessary for safety and help the analysis process to be cooperative and run smoothly until results are published. Provenance is also widely understood to be important, but the implications of changes in ecosystem services, especially in the unfortunately politicized context of climate change, make surety in one's data sources and methods with confidence in results even more critical. While I have an informed wariness of incorporating automation into scientific analysis, the currently supported level of automation in ESWS simply serves to filter based on data type, thereby easing the selection of parameter values. ESWS creates scalability in ecosystem service assessments by allowing simultaneous reading, writing, and execution of elements to reduce the time needed to run the workflow. In other systems, lack of such concurrency can block operations.

ESWS links are references to and metadata for ESWS elements. They augment ESWS element functionality inherent to OWS. This aids in interoperability and is the foundation for inter-element link flexibility. By using the established international OWS standards, ESWS lowers uptake costs and reduces platform lock-in. Fault tolerance improves reliability, especially in the absence of resource high availability. Transparency in ESWS comes from having elements in the cloud and conveys clarity about origins. Transparency is further complemented by a chain of custody that reveals how elements flow into and throughout ESWS. This approach to transparency is well suited for compliance and assists users with meeting disclosure requirements.

In the ecosystem service assessment context, data and methods can often come from different sources and the ability to use those together, because they are interoperable, is an essential precondition for analysis. Uptake costs and platform lock-in are always a concern, but especially so for ecosystem service assessment professionals who have to be budget conscious for themselves or clients while also desiring to have flexibility in using multiple or new platforms when justified. Justifying ESWS as a platform for facilitating the use of OWS requires added value and fault tolerance is one clear example. ESWS fault tolerance repeatedly attempts to access data and, when it is available, caches it for future use. Data for ecosystem service assessments can be provided by individuals, organizations, or government institutions that do not have permanent or reliable internet hosting. The ESWS fault tolerance capability can be critical for working with these kinds of data. Ecosystem service assessments often require multiple manual steps that can be tedious to document for transparency. In ESWS, all steps are recorded in the job history and can easily be referred to later. This documentation contains both the history and the analytical process including all references to methods and data, serving as a log that clearly conveys all provenance and simplifies transparency. This log, when taken as a whole, can be considered a chain of custody, which illuminates individual steps in an analysis as well as the overall process. Transparency and chain of custody are essential for compliance and assist analysts to meet disclosure requirements.

Combining ESWS elements and links forms workflows that can be modified and reused as needed. The ability to share these workflows with other scientists can assist in validation and collaboration when done interactively. This can lead to standardizing forms of analysis, improving defensibility, and aiding validation, continuation, and comparison studies. This also furthers scientific interests in the preservation and curation of knowledge.

For ecosystem service assessments, the ability to modify and reuse workflows is highly desirable because some ecosystem service models require calibration or benefit from repeated runs to determine optimal parameters and refine analysis. Assessments are often conducted in teams within and across research labs and being able to seamlessly share workflows along with all data and geoprocesses streamlines the collaboration process. Furthermore, having an omniscient view of the analysis process can allow each researcher to validate the approach, continue the analysis along another path, if appropriate, and make comparisons to other studies if available. This can reassure each researcher about the defensibility of every step of the workflow. Furthermore, with this level of clarity different studies can be more easily compared with the origins of differences in results made easier to determine.

6.4 Contributions to the SPI-I for ecosystem service assessments

The science-policy implementation interface is an interplay and feedback loop between scientists and policymakers. This requires an understanding on both their parts of the needs of the other and there are several ways in which ESWS can facilitate this exchange for ecosystem service assessments. Often of prime importance to policy makers is assessing the expected outcomes of scenarios, in addition to tracking actual outcomes. To that end, modularity serves as a way to examine alternative scenarios. Access control provides a means for highlighting the analysis elements suitable for discussion. Provenance serves as a means for tracking the sources of information and revealing oversights. Automation provides the mechanisms to select iterative elements identified in scenarios. Scalability allows for the scaling up of work to accommodate multiple scenarios. Interoperability provides the mechanism for being able to compare analysis elements.

Once the analysis elements for simulated and actual ecosystem services outcomes are identified, then there is a need to be able to link to these elements. The integration mechanism in ESWS enables the ability to bring analysis elements together. The use of OWS, as a free, open, and increasingly used standard, ensures flexibility. As the science-policy implementation interface matures and feedback between scientists and policy makers refines the scope and focus of the analysis, the flexibility to incorporate new and existing elements into an ecosystem service assessment is especially important. Fault tolerance in ESWS assures continued reliability in using and expanding on the scenarios agreed upon by scientists and policy makers. The transparency inherent to working with ESWS brings a clarity to the science-policy dialogue. The step-by-step transparency forms a chain of custody that lends certainty to the sources of analysis elements and helps fulfill compliance requirements.

Ultimately, after the scientists and policy makers have agreed on both the elements and structure of an ecosystem service assessment there is a need to carry out the analysis, including any comparative analysis, and to communicate results with stakeholders. This need is fulfilled by linking analysis elements into a workflow, which further serves as documentation of the entire analysis. With a cloud based ESWS workflow in hand, it can be shared to achieve the desired openness and transparency. Beyond sharing a workflow as a read only document, the workflow can also be shared with write and execution privileges for collaboration. Such collaboration can be continued as a dialogue among or between scientists and policy makers to iterate and achieve consensus.

6.5 Contributions to education on ecosystem service assessments

ESWS provides several features useful for increasing the education on ecosystem service assessments. The modularity of elements provides a mechanism for experimentation and tinkering that is highly useful for learners to understand the inner workings of an assessment and acquire spontaneous knowledge. Access control allows for the sharing of individual elements with the instructor for assistance and grading. The clear provenance demonstrates and documents the need for and way of including citations. The ability to create automations encourages the development of abstract thinking and programming skills. Interoperability provides capacity to select from a wide range of elements.

Links in ESWS contain references to ESWS elements and provides additional functionality on top of those already available from OWS. This ability to integrate many different elements, as is required in ecosystem service assessments, conveys flexibility and encourages creativity in learners. Learning about OWS through using ESWS provides students with skills that can be used in a variety of contexts. The fault tolerance mechanism teaches about the distribution of resources across a network and the topic of high availability while providing an avenue for developing troubleshooting skills. Transparency of linked elements creates clarity about the origins of resources. The chain of custody forms the basis of logic about how elements can be connected and presents an opportunity to develop reasoning skills, while the support for compliance through disclosure aids the instructor in evaluating a student.

Creation of workflows in ESWS for ecosystem service assessments brings together creativity, reasoning, and abstraction skills to give an overall clarity on how elements fit together. The ability to share this workflow allows the student to show all their work to the instructor to demonstrate their knowledge of the process that achieves their results or ask for assistance, if needed. The capacity for collaboration facilitates group projects. The ability to compare and contrast workflows among students, with the guidance of an instructor, can be used to understand the variety of pathways that can lead to similar results or, in some cases, come to a consensus on if there is only one way to arrive at an answer, and in either case forming some notion of the standard forms of an analytical process and supporting a basis for defensibility of the work.

6.6 Limitations

Based on the literature review and years of professional experience, specific opportunities for improving ecosystem service assessments for scientists, policy makers, and students were identified. These opportunities have been defined and detailed with concrete proposed solutions, which the ESWS framework could address. Nevertheless, there is more work to be done on and with ESWS. Surveys and user studies, as time intensive and challenging methods especially during the pandemic, which would more definitively identify the stated needs of scientists, policy makers, and students and reveal the effectiveness of ESWS have not been conducted. There are clear technical limitations of ESWS, the biggest of which is the limited number of integrated ecosystem service models. Furthermore, the user documentation for using ESWS is limited, and the developer documentation for modifying ESWS is nonexistent. One last area of scientific and technical interest would be to quantify the overhead of using OWS in ESWS to understand the computational costs.

6.7 Future Recommendations

ESWS shows substantial promise and should be taken past the proof-of-concept stage. To this end, future work should include incorporating more ecosystem service models, conducting user studies in science, policy, and education settings to evaluate if the expected benefits can be achieved, and creating a detailed developer guide to help and encourage others to create their own ESWS resources. Expanding on the ecosystem service model offerings in ESWS should include the terrestrial and marine models of InVEST building on past success and of special interest is incorporating SWAT+. As a test, a SWAT WPS server was created, but this only remotely triggered the running of an existing model. User studies with scientists and policy makers will require carefully identifying suitable participants and projects, but in an education setting there is clear pool of potential participants in the Ecosystem Service MOOC. The creation of a developer guide should be accompanied by utilities to help in ESWS publishing, such as the generation of process element templates by parsing code documentation strings. Lastly, a comparison of ESWS and non-ESWS workflows should be done to understand the relative computational costs of ESWS.

6.8 Concluding Remarks

Ecosystem service assessments are like a compass showing the directions we can sail in, towards one destination or away from another. This compass requires information and knowledge to understand but plotting and following a course, with the SDGs as a map, will only be possible with a collaboration between science, policy, and education. There is a profoundly urgent need to navigate to safer waters where our ecosystem will be more stable and that the hands at the helm will be steady for the long journey to recovery. My hopes are that ESWS can, in at least some small way, be part of that journey and, if not so directly, then at least as an example of how diverse resources, both human and technological, can be made stronger by bringing them together.

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APPENDICES

APPENDIX 1: CONTRIBUTING RESEARCH PAPERS

Title: A Framework for Ecosystem Service Assessment Using GIS Interoperability Standards

Authors: **Martin Lacayo**, Denisa Rodila, Gregory Giuliani, Anthony Lehmann

Abstract: Ecosystem Services Web Services (ESWS) are new web-based approaches to quantifying the benefits that humans derive from nature. Specifically, ESWS are the application of open web standards to ecosystem service assessment to facilitate creation, iteration, and dissemination in a seamless way. This integration streamlines collaboration, automation, and curation, while providing an open interface through which novel advances can be incorporated. The approach creates a new level of interoperability through data provenance whereby each transition between processing steps employs standards that ensure cohesive workflows across models and platforms. This imparts a modularity that can be examined and extended at every step.

DOI: https://doi.org/10.1016/j.cageo.2021.104821

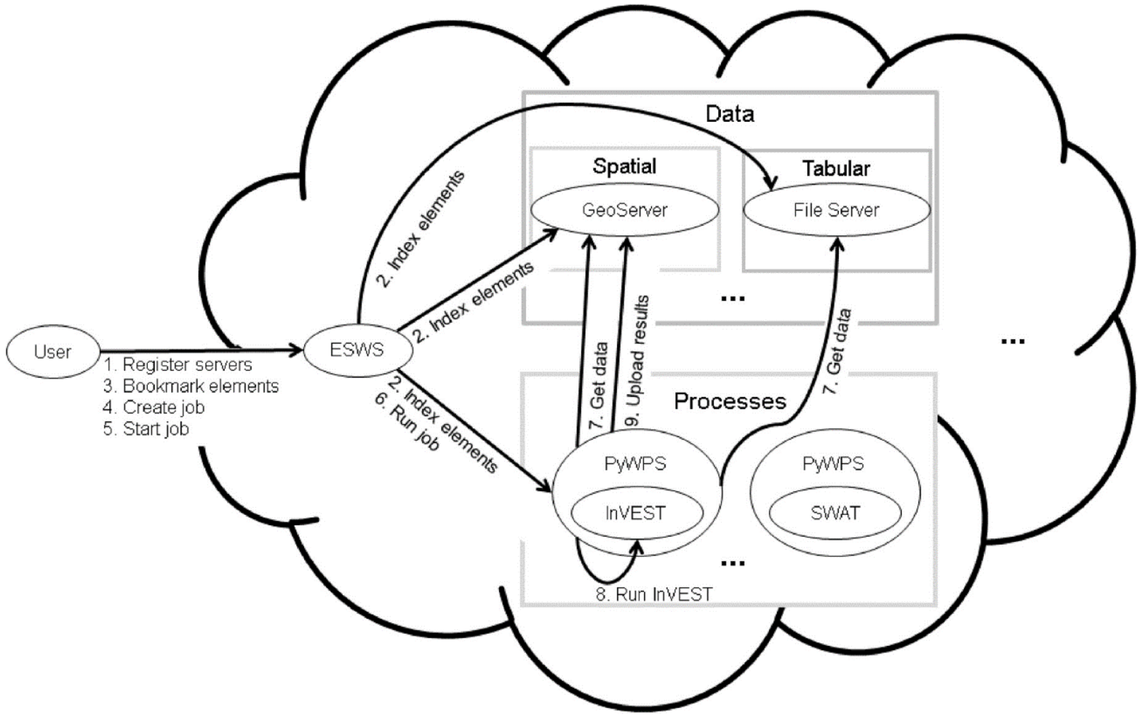


Figure: "SWATCH21: A project for linking eco-hydrologic processes and services to aquatic biodiversity at river and catchment levels"

Title: Impacts of Land-Use and Land-Cover Changes on Water Yield: A Case Study in Jing-Jin-Ji, China

Authors: Suxiao Li, Hong Yang, **Martin Lacayo**, Junguo Liu, Guangchun Lei

Abstract: Knowing the impact of land-use and land-cover (LULC) changes on the distribution of water yield (WY) is essential for water resource management. Using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, we investigated the spatial-temporal variations of WY from 1990 to 2015 in China's northern semi-arid region of Beijing–Tianjin–Hebei (Jing-Jin-Ji). We quantified the combined effects of LULC dynamics and climatic variation on WY. Furthermore, we identified the relative contribution of main LULC types to WY. For our study region, the built-up area increased by 35.66% (5380 km2) during the study period. In the meantime, cropland, grassland, and wetland decreased continuously. The expansion of built-up area and decline of vegetated land led to an increase of 1047 million m3 (5.1%) in total WY. The impacts of LULC changes on WY were mainly determined by the biophysical characteristics of LULC composition. Vegetated land has relatively lower WY coefficients due to higher rates of evapotranspiration and water infiltration. Built-up areas and bare land have higher WY coefficients as a result of their impermeable surface. The spatial-temporal analysis of WY with specification of WY coefficients by LULC types can facilitate integrated land-use planning and water resource management.

DOI: https://doi.org/10.3390/su10040960

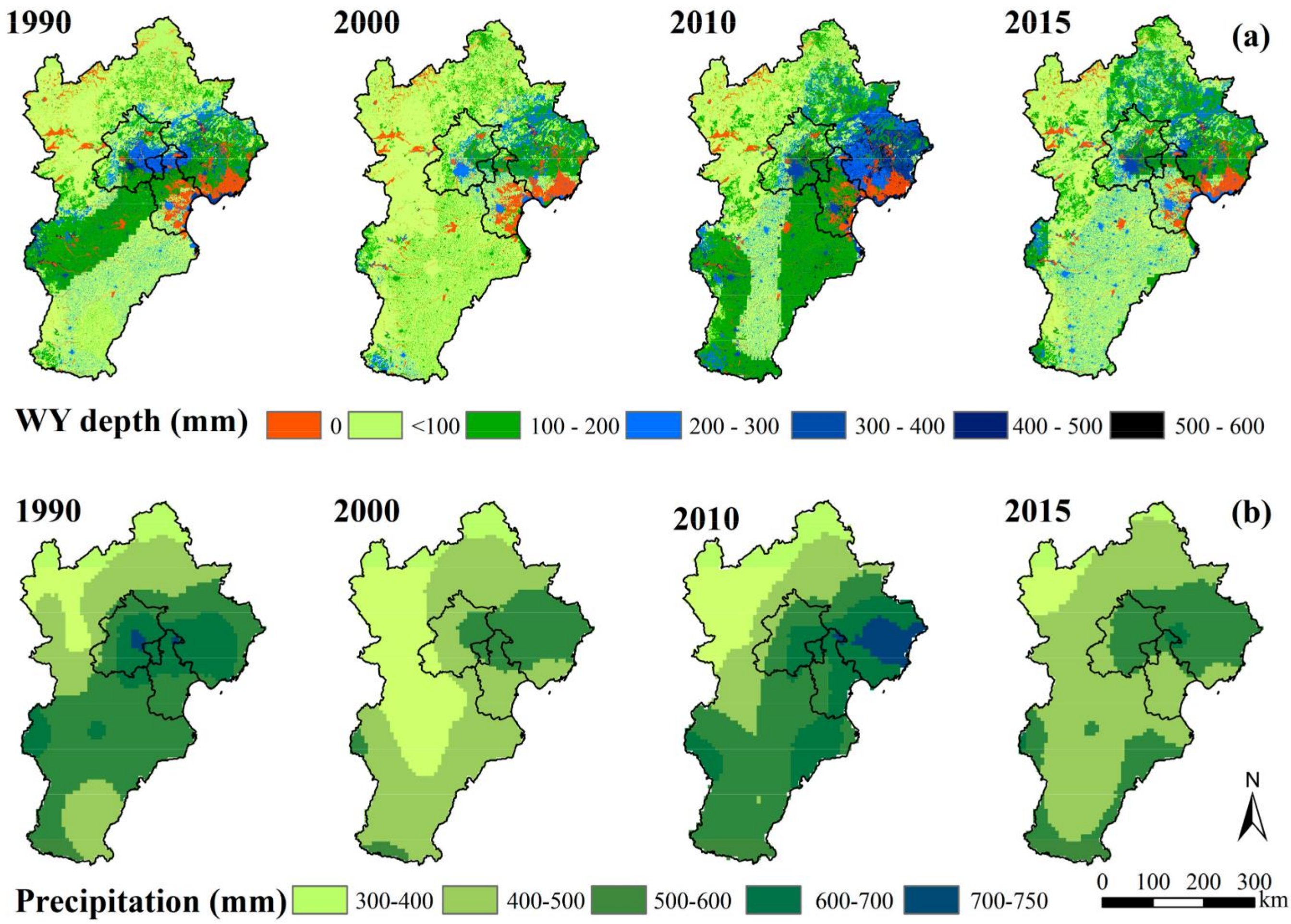


Figure 2. Spatial distribution of water yield (WY) (a), and average annual precipitation (b), of Jing-Jin-Ji from 1990 to 2015.

Title: Lifting the Information Barriers to Address Sustainability Challenges with Data from Physical Geography and Earth Observation

Authors: Anthony Lehmann, Rebecca Chaplin-Kramer, **Martin Lacayo**, Grégory Giuliani, David Thau, Kevin Koy, Grace Goldberg, Richard Sharp Jr.

Abstract: Sustainability challenges demand solutions, and the pace of technological and scientific advances in physical geography and Earth observation have great potential to provide the information needed to address these challenges. This paper highlights five online tools and initiatives that are lifting barriers to address these challenges. The enviroGRIDS project in the Black Sea catchment demonstrates how the use of spatial data infrastructures can facilitate data sharing. Google Earth Engine is providing solutions to challenges of processing big data into usable information. Additionally, application programming interfaces allow outsiders to elaborate and iterate on programs to explore novel uses of data and models, as seen in the Berkeley Ecoinformatics Engine. Finally, collaborative mapping tools, such as Seasketch/MarineMap and the InVEST software suite, allow engagement within and between groups of experts and stakeholders for the development, deployment, and long-term impact of a project. Merging these different experiences can set a new standard for online information tools supporting sustainable development from evidence brought by physical geography combined with socioeconomic conditions.

DOI: https://doi.org/10.3390/su9050858

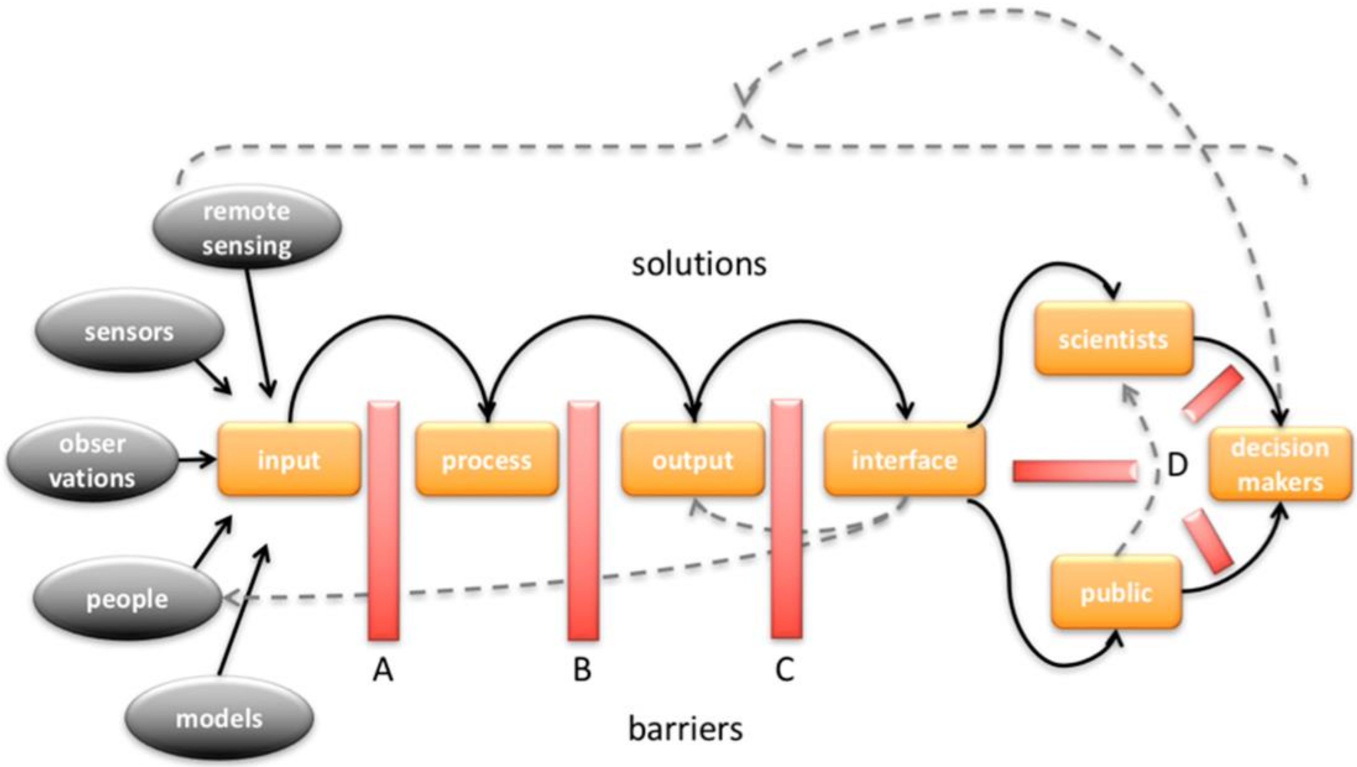


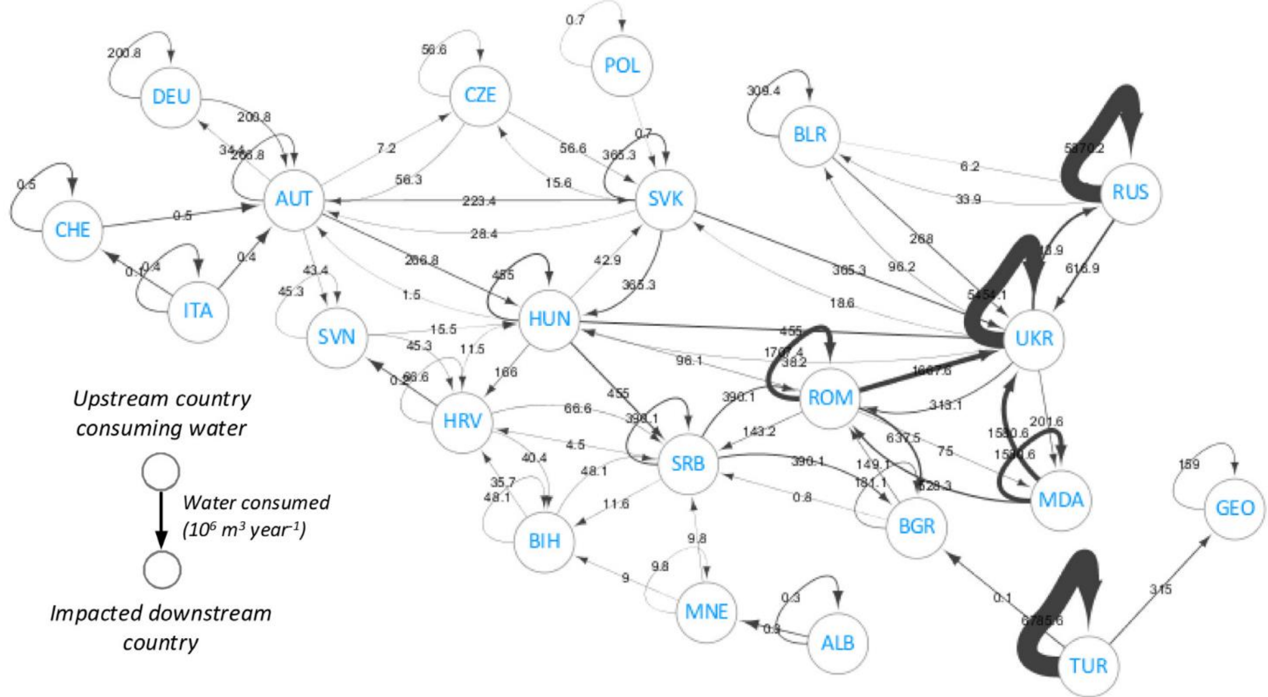
Figure 2. Barriers and solutions in the workflow from data to decision making for sustainability. (A) data access; (B) data size; (C) ability to elaborate and iterate existing software; and (D) knowledge transmission. Plain arrows represent solutions to lift barriers and dotted arrows represent active feedback in the workflow.

Title: Blue Water Scarcity in the Black Sea Catchment: Identifying Key Actors in the Water-Ecosystem-Energy-Food Nexus

Authors: Marc Fasel, Christian Bréthaut, Elham.Rouholahnejad, **Martin Lacayo**, Anthony Lehmann

Abstact: Large-scale water scarcity indicators have been widely used to map and inform decision makers and the public about the use of river flows, a vital and limited renewable resource. However, spatiotemporal interrelations among users and administrative entities are still lacking in most large-scale studies. Water scarcity and interrelations are at the core of the water-ecosystem-energy-food nexus. In this paper, we balance water availability in the Black Sea catchment with requirements and consumptive use of key water users, i.e., municipalities, power plants, manufacturing, irrigation and livestock breeding, accounting for evaporation from major reservoirs as well as environmental flow requirements. We use graph theory to highlight interrelations between users and countries along the hydrological network. The results show that water scarcity occurs mainly in the summer due to higher demand for irrigation and reservoir evaporation in conjunction with relatively lower water resources, and in the fall-winter period due to lower water resources and the relatively high demand for preserving ecosystems and from sectors other than irrigation. Cooling power plants and the demands of urban areas cause scarcity in many isolated locations in the winter and, to a far greater spatial extent, in the summer with the demands for irrigation. Interrelations in water scarcity-prone areas are mainly between relatively small, intra-national rivers, for which the underlying national and regional governments act as key players in mitigating water scarcity within the catchment. However, many interrelations exist for larger rivers, highlighting the need for international cooperation that could be achieved through a water-ecosystem-energy-food nexus.

DOI: https://doi.org/10.1016/j.envsci.2016.09.004



ALB = Albania; AUT = Austria; BLR = Belarus; BIH = Bosnia and Herzegovina; BGR = Bulgaria; HRV = Croatia; CZE = Czech Republic; GEO = Georgia DEU = Germany; HUN = Hungary; ITA = Italy; MKD = Macedonia; MDA = Moldova; MNE = Montenegro; POL = Poland; ROM = Romania RUS = Russia; SRB = Serbia; SVK = Slovakia; SVN = Slovenia; CHE = Switzerland; TUR = Turkey; UKR = Ukraine

Fig. 6. Relations among adjacent countries in terms of water consumptive use.

Title: Using Social Media to Quantify Nature-Based Tourism and Recreation

Authors: Spencer A. Wood, Anne D. Guerry, Jessica M. Silver, **Martin Lacayo**

Abstract: Scientists have traditionally studied recreation in nature by conducting surveys at entrances to major attractions such as national parks. This method is expensive and provides limited spatial and temporal coverage. A new source of information is available from online social media websites such as flickr. Here, we test whether this source of “big data” can be used to approximate visitation rates. We use the locations of photographs in flickr to estimate visitation rates at 836 recreational sites around the world and use information from the profiles of the photographers to derive travelers' origins. We compare these estimates to empirical data at each site and conclude that the crowd-sourced information can indeed serve as a reliable proxy for empirical visitation rates. This new approach offers opportunities to understand which elements of nature attract people to locations around the globe and whether changes in ecosystems will alter visitation rates.

DOI: https://doi.org/10.1038/srep02976

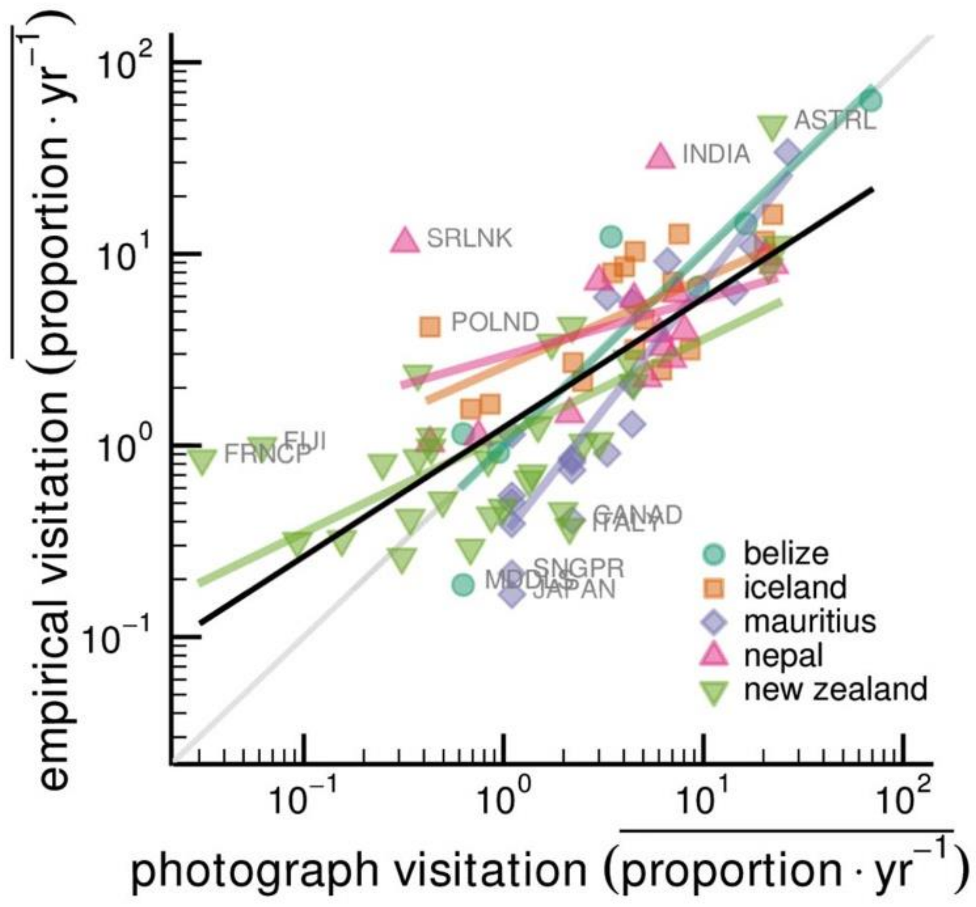


Figure 5 | The average proportion and originating country of travelers who arrived to five destination countries each year, according to stated home locations of flickr users who took at least one photograph within the country (x-axis) and immigration data (y-axis). Names of outlying originating countries are abbreviated. Datasets are distinguished by colors and symbols and described in Supplementary Table S2. Black line depicts the overall trend across all sites. Grey line is 1⁄51.

Title: Coastal Habitats Shield People and Property from Sea-Level Rise and Storms

Authors: Katie K. Arkema, Greg Guannel, Gregory Verutes, Spencer A. Wood, Anne Guerry, Mary Ruckelshaus, Peter Kareiva, **Martin Lacayo**, Jessica M. Silver

Abstract: Extreme weather, sea-level rise and degraded coastal ecosystems are placing people and property at greater risk of damage from coastal hazards. The likelihood and magnitude of losses may be reduced by intact reefs and coastal vegetation1, especially when those habitats fringe vulnerable communities and infrastructure. Using five sea-level-rise scenarios, we calculate a hazard index for every 1 km2 of the United States coastline. We use this index to identify the most vulnerable people and property as indicated by being in the upper quartile of hazard for the nation's coastline. The number of people, poor families, elderly and total value of residential property that are most exposed to hazards can be reduced by half if existing coastal habitats remain fully intact. Coastal habitats defend the greatest number of people and total property value in Florida, New York and California. Our analyses deliver the first national map of risk reduction owing to natural habitats and indicates where conservation and restoration of reefs and vegetation have the greatest potential to protect coastal communities.

DOI: https://doi.org/10.1038/NCLIMATE1944

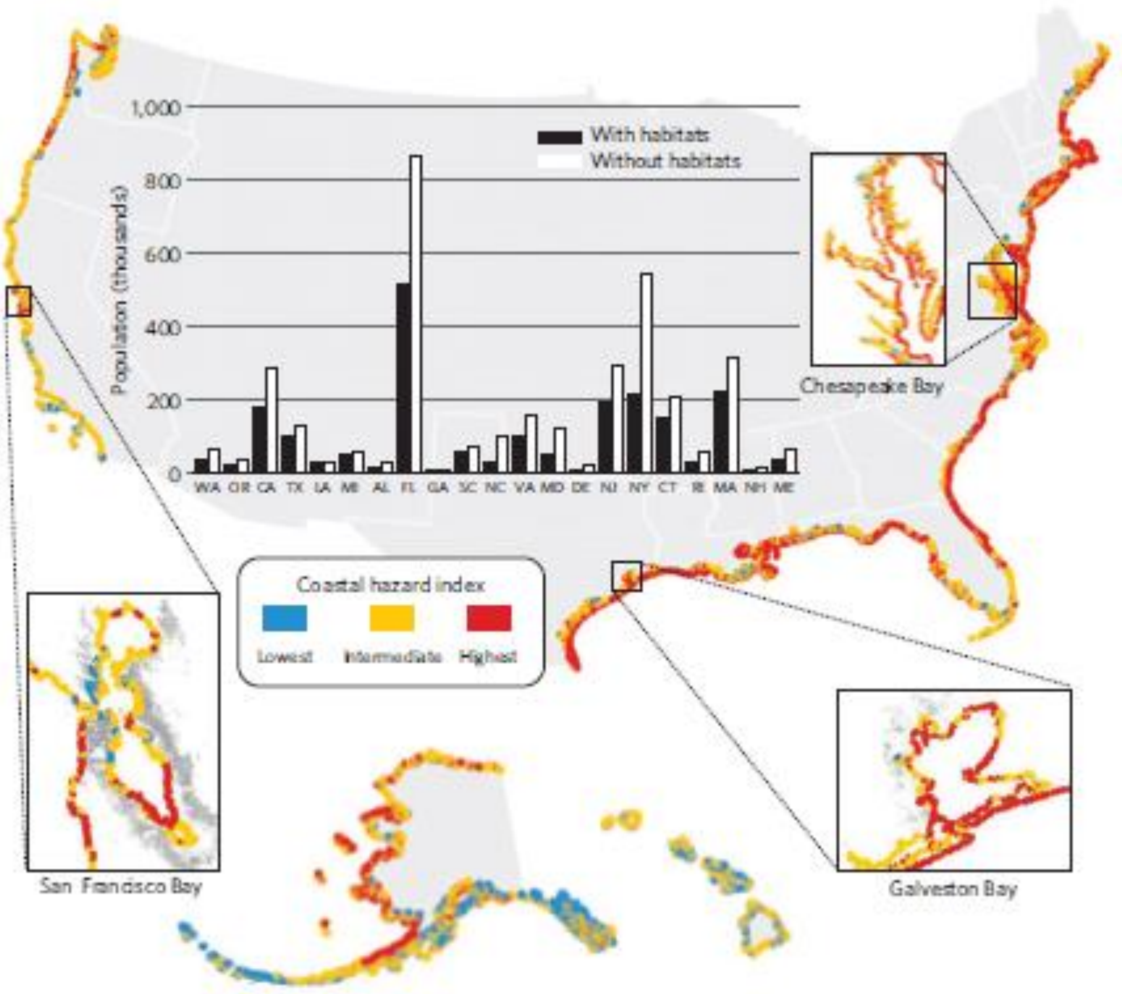


Figure 2 | Exposure of the US coastline and coastal population to sea-level rise in 2100 (A2 scenario) and storms. Warmer colours indicate regions with more exposure to coastal hazards (index >3.36). The bar graph shows the population living in areas most exposed to hazards (red 1 km2 coastal segments in the map) with protection provided by habitats (black bars) and the increase in population exposed to hazards if habitats were lost owing to climate change or human impacts (white bars). Letters on the x axis represent US state abbreviations. Data depicted in the inset maps are magnified views of the nationwide analysis.

APPENDIX 2: EDUCATIONAL GAME

https://esgame.unige.ch/

Tradeoff: Agriculture edition!

Instructions:

Farms and ranches generate income, but they also have negative impacts on local ecosystems and species. Although this information was not available to you during Round 1, the negative effects still took place. Look at the four new maps that illustrate the negative impacts of your choices on four ecosystem services. Your Round 1 Net Score integrates these externalities. Sad!

Your objective in Round 2 will be to maximize your Net Score. Do this by removing your farms and ranches (by clicking on them) and then re-making them in places that strike a better balance between their revenue and externalities (costs). Remember to use the "Make" toggle to switch between making ranches and farms. Also note that the scale of the costs varies depending on the activity.

The game is finished when you are satisfied with your net score. Were you able to reduce the externalities relative to Round 1? Did that mean reducing income as well? You should be able to reach a Net Score of at least 4100, but 4600 is even better.

Take home message:

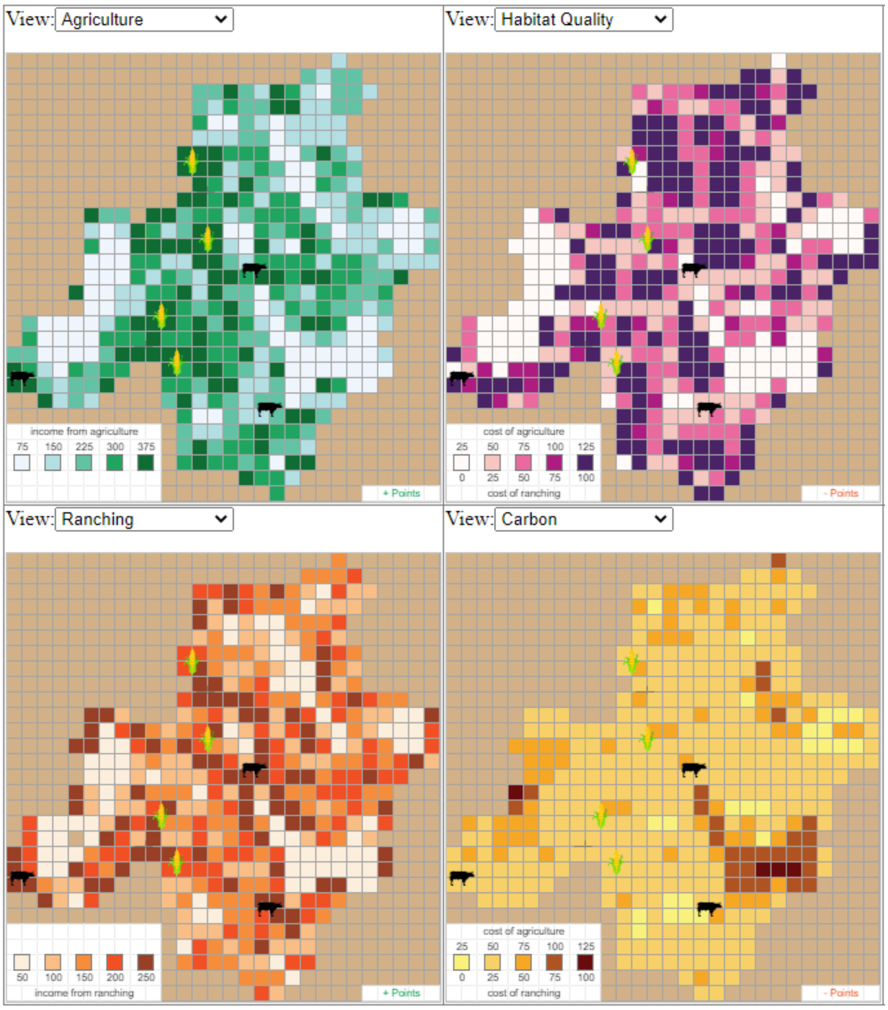
Decisions that impact natural resources sometimes do not consider the full value of what is being lost when land is converted for commercial purposes. In the absence of other sources of information, decisions will seek to generate income (Round 1). The ecosystem service approach can help by providing additional information (Round 2) that can then become an integral part of this planning process, thus creating a better balance of values for people and nature.

Round 1 Score

			Agriculture		Ranching			
			5925	+	3750	=	9675	
Habitat Quality		Carbon Storage	Hunting and Foraging		Water Quality			
-2075	+	-1300	+ -1050	+	-1150	=	-5575	
					Net	=	4100	

Round 2 Score

			Agriculture		Ranching			
			5925	+	2750	=	8675	
Habitat Quality		Carbon Storage	Hunting and Foraging		Water Quality			
-1625	+	-1200	+ -1150	+	-1150	=	-5125	
					Net	=	3550	



APPENDIX 3: MOOC

https://www.coursera.org/learn/ecosystem-services

Ecosystem Services: a Method for Sustainable Development

About this Course:

Ecosystem services are a way of thinking about – and evaluating – the goods and services provided by nature that contribute to the well-being of humans.

This MOOC will cover scientific (technical), economic, and socio-political dimensions of the concept through a mix of theory, case-studies, interviews with specialists and a serious-game. By the end of this course, our aim is to enable you to:

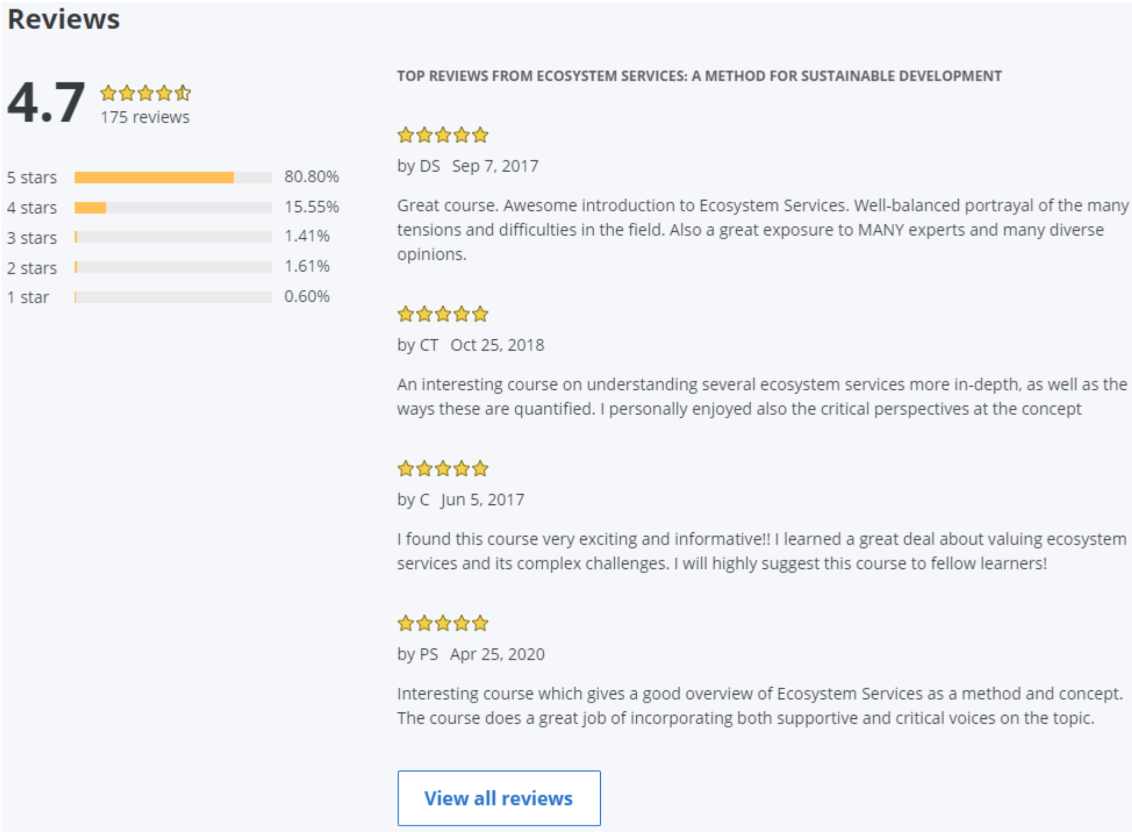
- define the concept of ecosystem services, its principles and limitations
- understand the key services associated with any ressource (e.g., fresh water) through readings and case-studies
- appreciate the advantages and potential risks of monetising ecosystem services
- appreciate the social dimensions (power issues, cultural biases) embedded within any method
- integrate tactical advice on mainstreaming this approach into policy and standard government practices
- Optional: learn how to map ecosystem services with GIS tools

The session that runs May 29th- July 10th will be actively monitored by the instructors, and learners will have the opportunity to ask questions.

This course was developed by instructors from the University of Geneva with the help of numerous researchers and input from the Geneva Water Hub and the Natural Capital Project. The course was financed by the University of Geneva, the Global Programme Water Initiatives of the Swiss Agency for Development and Cooperation (SDC), and the Luc Hoffmann Institute.

This MOOC is supported by the Geneva Water Hub and the University of Geneva along with the MOOC in « Water Resources Management and Policy » (www.coursera.org/learn/water-management) and the one in « International Water Law » (www.coursera.org/learn/droit-eau).

We look forward to you joining us!



28,184 already enrolled

APPENDIX 4: InVEST WATER YIELD ASSESSMENT TUTORIAL

A 60 page step by step tutorial for gathering and preprocessing data in QGIS for the InVEST Water Yield model followed by instructions on how to visualize the results in QGIS.
https://esws.unige.ch/tut.html

For example, preprocessing the precipitation data is given as follows.

The precipitation comes from WorldClim dataset.

Use **Layer > Add Layer > Add Vector Layer** to add all 12 precipitation rasters to QGIS.
Use **Raster > Raster Calculator** to create wc.tif by adding together all 12 precipitation rasters using the + operator.

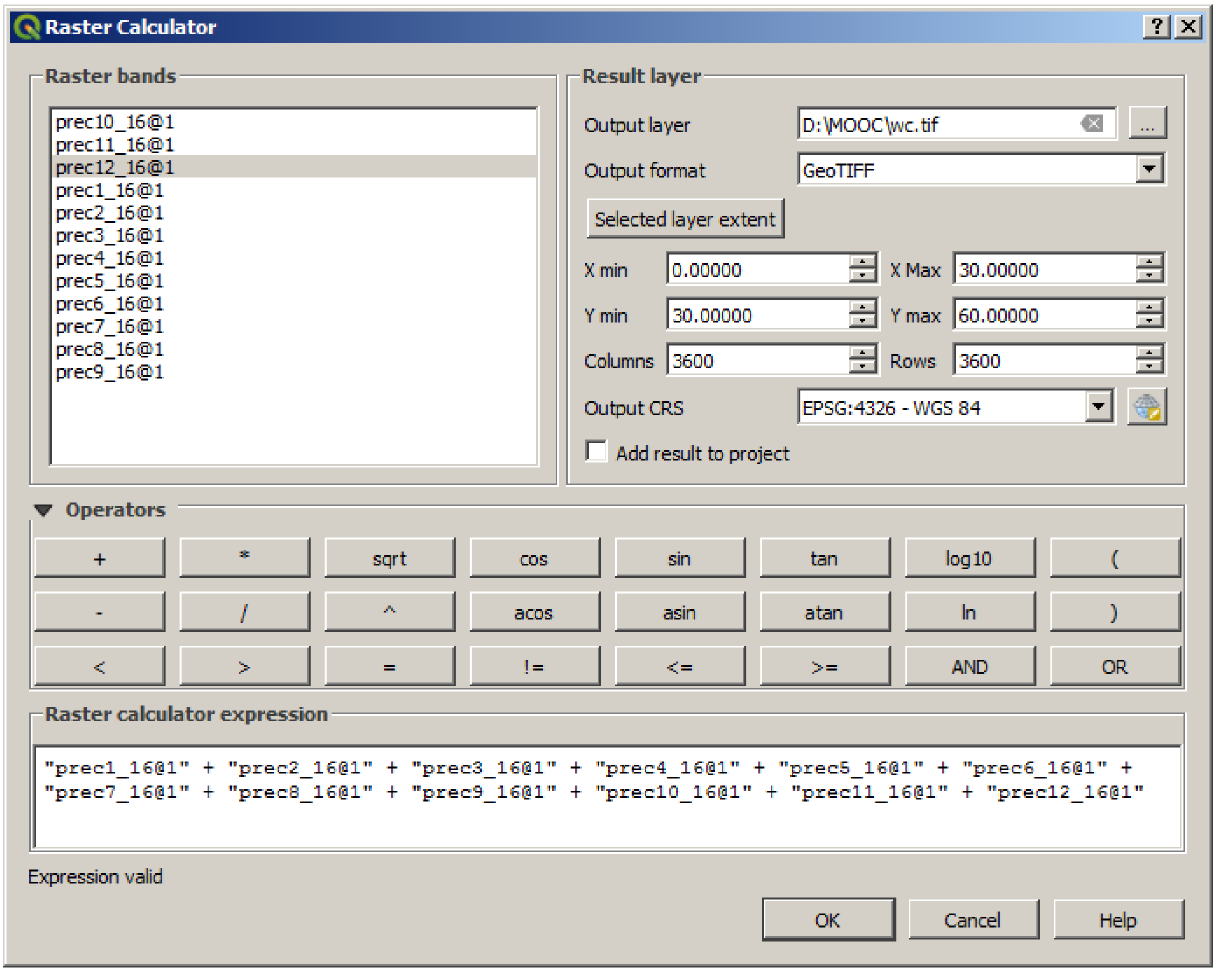


Figure 1 Screenshot of QGIS raster calculator dialog box for annual precipitation

1. Use **Raster > Extraction > Clip Raster by Mask Layer** to create wc_aoi.tif by clipping wc.tif with aoi.shp.

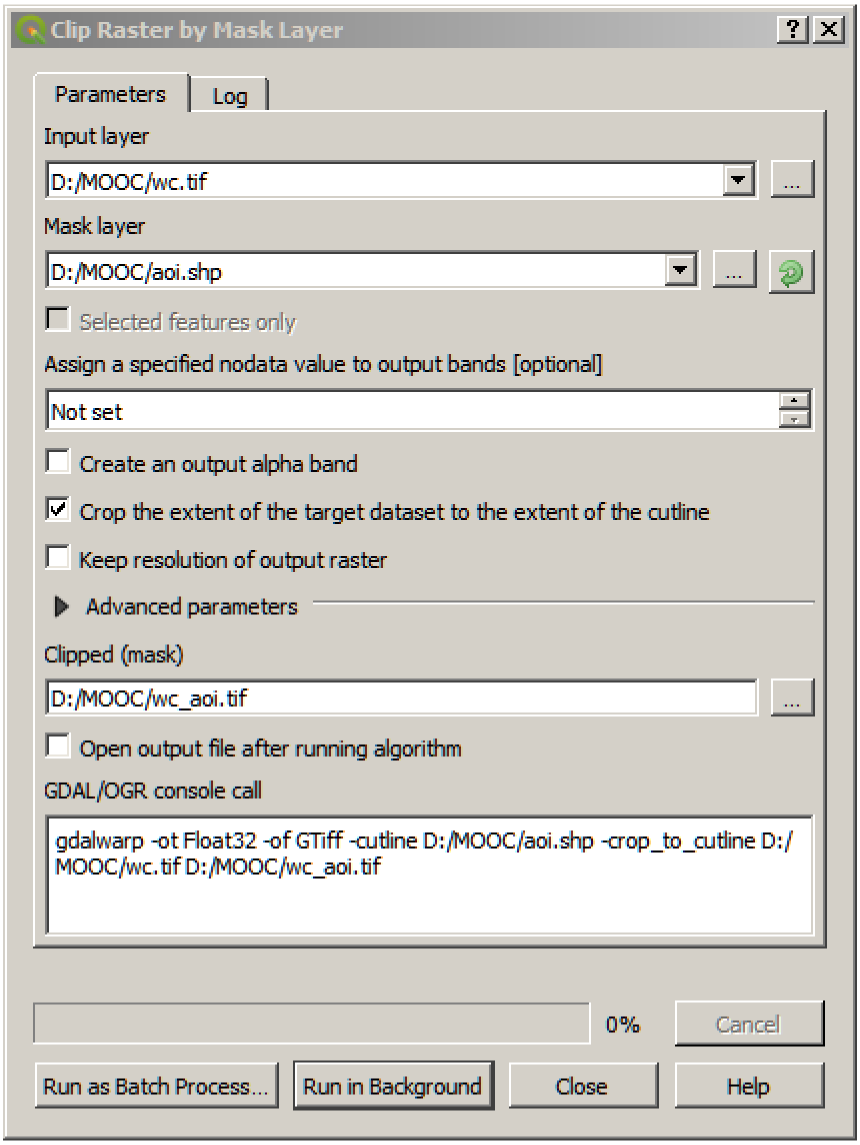


Figure 2 Screenshot of QGIS clip raster by mask layer dialog box for area of interest annual precipitation

2. Use **Raster > Projections > Warp (Reproject)** to create precip.tif by projecting wc_aoi.tif to the analysis projection EPSG:32632.

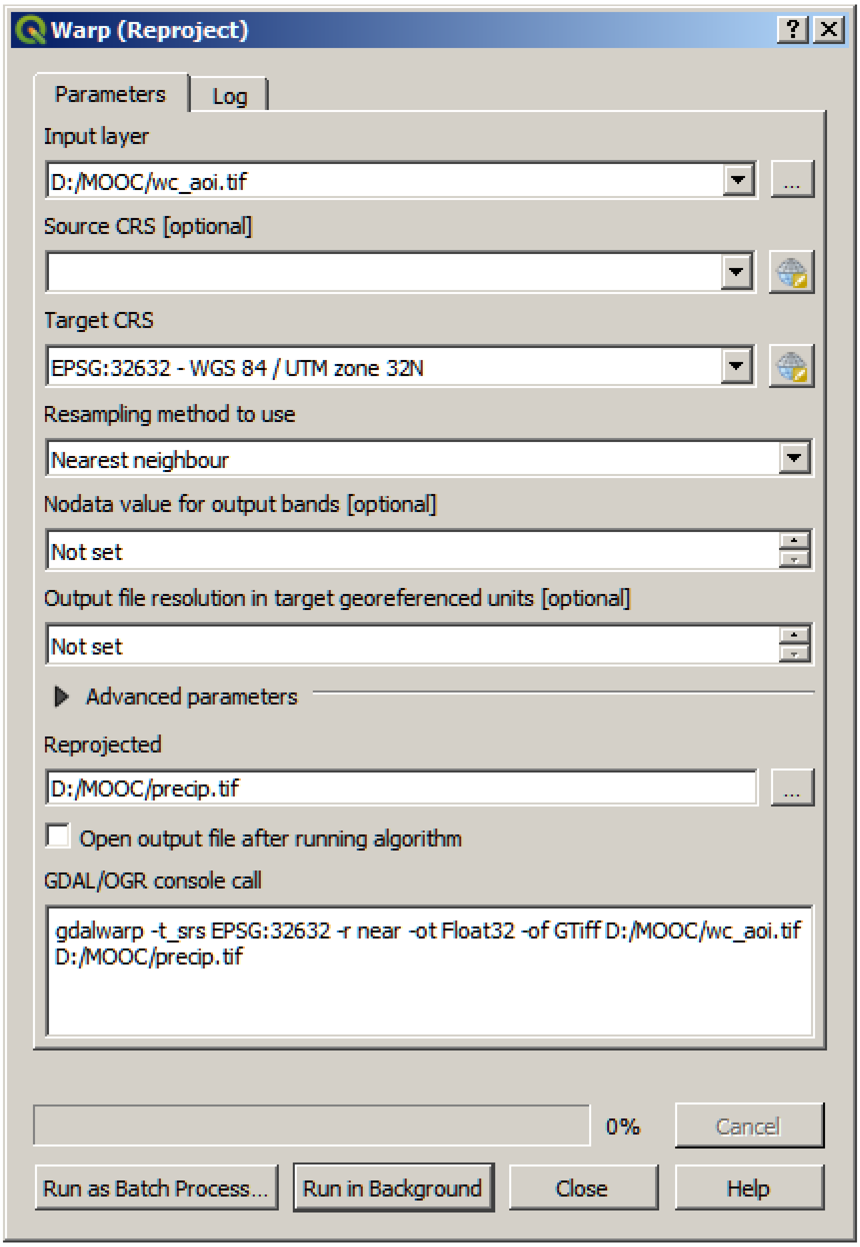


Figure 3 Screenshot of QGIS warp raster dialog box for reprojected area of interest annual precipitation

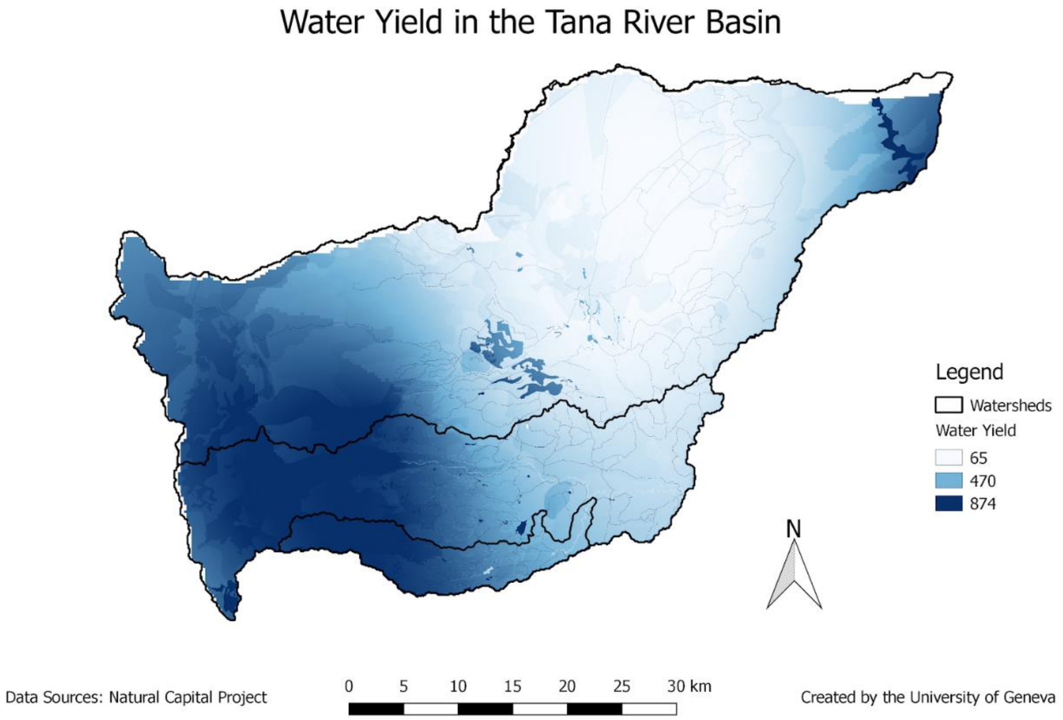


Figure 5: Map of example InVEST water yield model

APPENDIX 5: ESWS DOCUMENTATION

https://esws.unige.ch

ESWS

Navigation

- Installation
- Running
- Configuration & Maintenance
- Tabular Data
- Raster Data
- Vector Data
- Processes
- Third-Party Extensions
- Tutorials

Quick search

Go

Ecosystem Service Web Service

Ecosystem Service Web Service (ESWS) is a method for creating interoperable analysis workflows with the Open Geospatial Consortium (OGC) Web Services (OWS) standards , especially the Table Join Service (TJS), Web Coverage Service (WCS), Web Feature Service (WFS), and Web Processing Service (WPS).

ESWS workflows are:

- modular
- redistributable
- open

Resources:

- VirtualBox 6.0 virtual machine (OVA)
- GitHub Repository

LIST OF FIGURES, TABLES, WEBSITES, & ABBREVIATIONS

Figures

Tables

Websites

EcoPotential	http://www.ecopotential-project.eu
EcoPotential funding	https://cordis.europa.eu/project/id/641762
GEOEssentials	http://www.geoessential.eu
GEOEssentials funding	https://cordis.europa.eu/project/id/689443
SWATCH21	https://www.unige.ch/envirospace/projects/swatch21
SWATCH21 funding	http://p3.snf.ch/project-173206
Millennium Ecosystem Assessment	http://www.millenniumassessment.org
The Economics of Ecosystems and Biodiversity	http://www.teebweb.org
Common International Classification of Ecosystem Services	https://cices.eu
Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services	https://www.ipbes.net

ABBREVIATIONS AND ACRONYMS

AGILE	Association of Geographic Information Laboratories in Europe
API	Application programming interface
ARIES	Artificial Intelligence for Ecosystem Services
BIOMOD	BIOdiversity MODelling
CARET	Classification And REgression Training
CSV	Comma separated values
DIKW	Data Information Knowledge Wisdom
EEA	European Union Land and Ecosystem Accounts
EPT	Ephemeroptera, Plecoptera and Trichoptera
ES	Ecosystem services
ESWS	Ecosystem Service Web Service
FAO	(United Nations) Food and Agriculture Organization
FTP	File transfer protocol
GCMD	Global Change Master Directory
GAM	Generalized additive models
GDM	Generalized dissimilarity modeling
GLM	Generalized linear models
GEO	Group on Earth Observation
GEO DAB	Group on Earth Observation Discovery and Access Broker
GEOSS	Global Earth Observation System of Systems
GFCS	Global Framework for Climate Services
GIScience	Geographic Information Science
GLM	Generalized linear models
GRASP	Generalized regression analysis and spatial prediction
HTTP	Hypertext Transfer Protocol
HydroSHEDS	Hydrological data and maps based on SHuttle Elevation Derivatives
INSPIRE	Infrastructure for Spatial Information in the European Community
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
ISO 19115	International Organization for Standardization standard 19115
ISRIC	International Soil Reference and Information Centre
LULC	Land use land cover change

MAXENT	Maximum entropy estimation
NASA	(US) National Aeronautics and Space Administration
NDR	Nutrient delivery ratio
OGC	Open Geospatial Consortium
OPAL	Offset Portfolio Analyzer and Locator
OWS	Open Geospatial Consortium web services
PET	Potential evapotranspiration
REST	Representational state transfer
RIOS	Resource Investment Optimization System
SaaS	Software as a service
SDI	Spatial Data Infrastructure
SDGs	Sustainable Development Goals
SDM	Species Distribution Modeling
SDR	Sediment delivery ratio
SWAT	Soil and Water Assessment Tool
SWATCH21	Soil and Water Assessment Tool project for Switzerland in the 21st century
TJS	Table Joining Services
UN	United Nations
URL	Uniform Resource Locator
USGS	United States Geological Survey
WCS	Web Coverage Service
WFS	Web Feature Service
WPS	Web Processing Service
WY	Water yield
XML	Extensible Markup Language
GIS	Geographic Information Systems