Science of the Total Environment 650 (2019) 2325–2336

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Towards globally customizable ecosystem service models

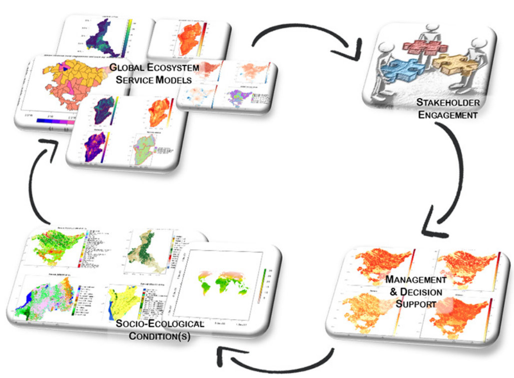
Javier Martínez-López [a,*], Kenneth J. Bagstad [b], Stefano Balbi [a], Ainhoa Magrach [a], Brian Voigt [c], Ioannis Athanasiadis [d], Marta Pascual [a], Simon Willcock [e], Ferdinando Villa [a,f]

[a] BC3-Basque Centre for Climate Change, Sede Building 1, 1st floor, Scientific Campus of the University of the Basque Country, 48940 Leioa, Spain
[b] U.S. Geological Survey, Geosciences & Environmental Change Science Center, PO Box 25046, MS 980, Denver, CO 80225, USA
[c] University of Vermont, Gund Institute for the Environment, 617 Main Street, Burlington, VT 05405, USA
[d] Information Technology Group, Wageningen University, the Netherlands
[e] School of Environment, Natural Resources and Geography, Bangor University, United Kingdom
[f] IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

HIGHLIGHTS

- Ecosystem service (ES) modeling is typically time consuming.
- Limited data and model reuse hinder new applications and progress in the field.
- We demonstrate 5 cloud-based ARIES models that can run on global or customized data.
- Models produce consistent outputs, including ES supply, demand and surplus/deficit.
- Community-level data and model sharing can advance progress in ES modeling.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 19 June 2018
Received in revised form 16 September 2018
Accepted 30 September 2018
Available online 01 October 2018

Editor: Damia Barcelo

Keywords:
ARIES
Cloud-based modeling
Context-aware modeling
Decision making
Semantic modeling
Spatial multi-criteria analysis

ABSTRACT

Scientists, stakeholders and decision makers face trade-offs between adopting simple or complex approaches when modeling ecosystem services (ES). Complex approaches may be time- and data-intensive, making them more challenging to implement and difficult to scale, but can produce more accurate and locally specific results. In contrast, simple approaches allow for faster assessments but may sacrifice accuracy and credibility. The ARtificial Intelligence for Ecosystem Services (ARIES) modeling platform has endeavored to provide a spectrum of simple to complex ES models that are readily accessible to a broad range of users. In this paper, we describe a series of five “Tier 1” ES models that users can run anywhere in the world with no user input, while offering the option to easily customize models with context-specific data and parameters. This approach enables rapid ES quantification, as models are automatically adapted to the application context. We provide examples of customized ES assessments at three locations on different continents and demonstrate the use of ARIES' spatial multi-criteria analysis module, which enables spatial prioritization of ES for different beneficiary groups. The models described here use publicly available global- and continental-scale data as defaults. Advanced users can modify data input requirements, model parameters or entire model structures to capitalize on high-resolution data and context-specific model formulations. Data and methods contributed by the research community become part of a growing knowledge base, enabling faster and better ES assessment for users worldwide. By engaging with the ES modeling community to further develop and customize these models based on user needs,

* Corresponding author.
E-mail address: javier.martinez@bc3research.org (J. Martínez-López).

https://doi.org/10.1016/j.scitotenv.2018.09.371

spatiotemporal contexts, and scale(s) of analysis, we aim to cover the full arc from simple to complex assessments, minimizing the additional cost to the user when increased complexity and accuracy are needed.

1. Introduction

Over a decade after the publication of the Millennium Ecosystem Assessment (MEA, 2005), ecosystem service (ES) modeling is slowly becoming a more mature field. Abundant examples of ES modeling applications from local to global scales now exist (Maes et al., 2015; Ochoa and Urbina-Cardona, 2017). Large-scale, global assessments are also driven by policy needs that support initiatives such as the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES; Pascual et al., 2017), the U.N. Sustainable Development Goals (SDGs; U.N., 2017), and natural capital accounting, including wealth accounts and the System of Environmental-Economic Accounting (Bagstad et al., 2018b; U.N., 2014).

Ideally, the next generation of ES models will be accessible and rapid, yet customizable, efficiently reusing place-specific data and knowledge. Reducing the effort needed to produce an ES assessment is important for delivering timely results to decision makers and stakeholders, so that ES information does not arrive after the decision window has closed (Ruckelshaus et al., 2015). Model and data customization are important for capturing local knowledge, improving credibility, and reducing the inherent inaccuracies of global and other large-scale data (Cerretelli et al., 2018; Zulian et al., 2018). Ideally, customization would extend beyond input data to include model structure, accounting for key differences in how ES are generated (Smith et al., 2017) and used by people (Wolff et al., 2017). Customizable ES models capable of synthesizing and reusing dispersed knowledge could help break from the long-standing dichotomy of using one-size-fits-all versus place-based approaches for ES assessments (Carmen et al., 2018; Rieb et al., 2017; Ruckelshaus et al., 2015).

In recognition of these limitations, efforts are underway to adapt ES modeling platforms for global application, e.g., ARtificial Intelligence for Ecosystem Services (ARIES; Villa et al., 2014), Co$ting Nature (Mulligan, 2015), and Integrated Valuation of Ecosystem Services Tradeoffs (InVEST; Sharp et al., 2015). Co$ting Nature is a web-based tool with preloaded models and datasets that supports ES assessment anywhere on Earth. Version 3.0 (currently in beta) enables the assessment of 12 ES, but does not support model customization by users. Moreover, options to run analyses at moderate to high resolution and output results in biophysical units rather than index values require a paid subscription. InVEST's global application adapts their existing suite of models (Sharp et al., 2015) in a development build based on InVEST 3.4.4, incorporating global datasets and model coefficients (Kim et al., 2018). While the InVEST global models are under development, the model code and coefficients are available from a publicly available code repository and the input data are available as described by Kim et al. (2018). Few of these large-scale modeling platforms enable customization with local data, parameterizations, or adjustments to model structure to reflect local knowledge of processes that underlie ES supply and demand. For example, Kim et al. (2018) apply a global mean parameter dataset to running InVEST. Zulian et al. (2018) provide an example of the customization of the Ecosystem Services Mapping Tool (ESTIMAP), a European ES modeling platform (Maes et al., 2015), and provide guidelines to make model customization more scientifically robust and decision relevant. However, the source code of the models is not yet publicly available and cannot be directly reused or adapted by users.

In this paper, we describe the ARIES modeling platform's approach to developing global, yet customizable ES models. Our approach endeavors to balance tensions between the demand for complexity, through model customization and data integration to reflect biophysical and socioeconomic conditions and behaviors, and simplicity, as data limitations and user needs may require abstraction and simplification of some ES models. Simple ES models are suitable to support some resource management decisions (Willcock et al., 2016), while others require information generated by more complex models. As such, the linking of simple and complex ES models can help support adaptive management by providing timely information that can easily be updated and reevaluated as new data and knowledge become available. In this paper, we describe models that can provide a "bottom line" strategy for rapid assessment and prioritization, while ensuring consistency in outputs among different ES and adaptability to trade-off analysis, as the first tier of a seamless path to adaptive complexity and automated integration of ES models (Villa et al., 2014).

Our approach to automated model customization expands the role of global ES models, enabling navigation between different model tiers based on ES assessment needs, time and data availability. A "Tier 1" approach, analogous to tiered approaches to forest carbon monitoring under Reducing Emissions from Deforestation and Forest Degradation (REDD+; Angelsen et al., 2012), ES models proposed in InVEST (Kareiva, 2011) and other environmental modeling approaches (Günther et al., 2013), is interpreted here as a base for customization and a default strategy to use when better models (e.g., dynamic flow models; Bagstad et al., 2013) are not available. The ARIES model base also includes several Tier 2 models, such as a dynamic agent-based pollination model that quantifies flows of pollinators between habitat patches and pollination-dependent crops, and water supply models employing dynamic, distributed surface runoff simulation. Such models are currently too computationally intensive for large-scale application, and, like any modeling approach, require calibration if accurate outputs are desired. Once ARIES is supplied with decision rules about the appropriate scale and spatiotemporal context under which to run each model tier, it can seamlessly navigate between tiers as spatiotemporal context and resolution change, and as more data and models become available.

These Tier 1 models provide a baseline for subsequent specialization and customization. When semantically annotated data covering new spatial and temporal extents or resolutions are made available either locally on a user's computer or on the network, the annotated concept (Janowicz et al., 2015) described in the data enables ARIES to automatically substitute local data for global where appropriate (Villa et al., 2014, 2017). For instance, a local or national-scale dataset for "percent tree canopy cover" will replace a global dataset for the same observable when a model requires that input and is run in a compatible time and place. New models or adjustments to existing models can be specified for a particular time, place, or spatiotemporal scale, and may cover all concepts related to an ES or only a *component concept* of it (e.g., its supply or demand). Because ARIES is a *context aware* modeling system, the best available knowledge will be reused for the context analysed. The system assembles a computational strategy, based on a set of rules under which data, models, and model parameterizations are selectively applied (Villa et al., 2014), which is run to produce both the desired outputs and associated provenance information (Villa et al., 2014). The latter is compiled into a report detailing the provenance of all input data and the algorithms used to produce the modeled outputs (Willcock et al., 2018). We thus lay the foundation for an intelligent ES modeling platform that can improve model credibility by more systematically incorporating and reusing local knowledge (Zulian et al., 2018). As more data and models are shared on the semantic web used by ARIES, the accuracy, speed and credibility of ES assessments can be substantially improved.

This work supports progress towards several long-anticipated goals in ES modeling specifically and semantic modeling more generally