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PERSPECTIVE

The future of ecosystem assessments is automation, collaboration, and artificial intelligence

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1. Introduction

The world faces unprecedented environmental change, a global biodiversity crisis, and an urgent need for sustainable human development [1]. International and national bodies have set ambitious agendas to help overcome these environmental challenges, such as the United Nations' (UN) Decade on Ecosystem Restoration, the 2030 Agenda for Sustainable Development, and the pending conservation of 30% of U.S. land and ocean by 2030 (30 by 30). Promptly assessing the status of ecosystems worldwide is essential to evaluate whether we are meeting these programs' objectives and to identify where further progress and targeted action are needed. Ecosystem assessments enable necessary understanding of ecological status by synthesizing multiple aspects of ecological change, including relations between people and ecosystems. However, such assessments have major limitations, as they are often infrequent, multi-year projects that are difficult to repeat and have limited *in-situ* and human data integration.

International organizations, national agencies, and scientific networks are accelerating efforts to track the state and trajectory of ecosystems to inform these assessments [2]. Remarkable recent advances in data collection automation, cyberinfrastructure, and artificial intelligence (AI) offer extraordinary opportunities to surpass the limitations that hinder ecosystem assessments [3]. Yet, adopting and advancing these technologies for ecosystem assessments is prevented by difficulties in data integration, limited access to cyberinfrastructure, and an overall lack of standardization and reproducibility in data workflows. Surpassing these hurdles could transform ecosystem assessments into rapid, repeatable, and reproducible workflows that allow us to measure our advancement towards ecological objectives, ultimately improving our ability to adapt and optimize management strategies and monitor conservation outcomes to ensure long-term success.

We believe scientists, governments, international organizations, environmental non-governmental organizations, and tech industry leaders can take action and leverage technology to resolve current limitations of ecosystem assessments by focusing on: (a) developing rapid, reproducible, and repeatable data workflows, (b) harmonizing *in situ* and remotely sensed data, (c) integrating economic and biophysical data, and (d) increasing access to cyberinfrastructure and technical knowledge. By fostering open and strong collaborations among different disciplines

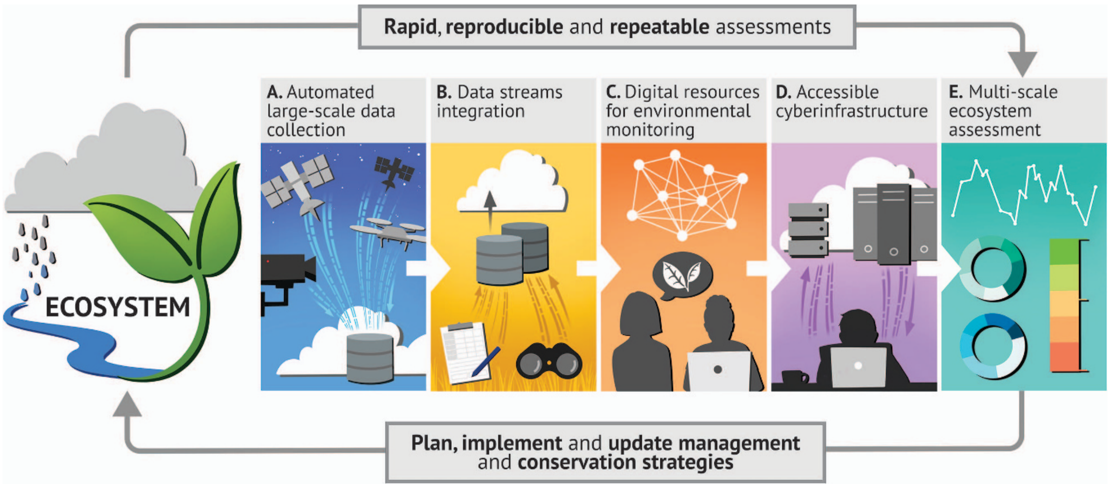

Figure 1. Rapid, reproducible, and repeatable ecosystem assessments powered by technological advances are urgently needed to accomplish global environmental management and conservation goals. The following points complement the sections explored in this article: (A) automating data collection through remote sensors coupled with cloud platforms for storage and efficient processing opens new opportunities to track large-scale biophysical change. (B) Validating and enriching remotely sensed data with field and socioeconomic information sources will be possible by standardizing data semantics and developing platforms that facilitate data integration. (C) Developing relevant digital resources for environmental analyses that incorporate diverse information sources will depend on collaborations combining technological and environmental knowledge, possibly incorporating expertise from academic, public, governmental, and private sectors. (D) Expanding environmental data analysis and storage platforms by using open-source software and increasing interoperability and ease of use can help more ecosystem assessments benefit from Big Data and cloud-based solutions. (E) Implementing streamlined ecosystem assessment workflows that can be updated as new data streams become available will enable multi-scale, regular, and transparent environmental monitoring.

and community sectors, we can accelerate the development and adoption of the technologies needed to conduct ecosystem assessments that will improve the management and conservation of ecosystems worldwide.

1.1. Rapid, reproducible, and repeatable data workflows

Comparing ecosystem assessments across space and time enables identification of location, magnitude, and direction of ecosystem change, a critical step in providing researchers and decision-makers the necessary information to plan, implement and update management and conservation strategies. However, time-consuming data discovery, processing, and analysis pose substantial barriers to conducting an assessment even once, let alone repeating it at the frequency needed to evaluate progress towards environmental goals and act on current information, particularly at regional to global scales. The UN's Millennium Ecosystem Assessment [4] in 2005 and the Intergovernmental Science-Policy Panel on Biodiversity and Ecosystem Services Global Assessment Report on Biodiversity and Ecosystem Services [1] in 2019 are examples of evaluations with slow turnaround and compatibility challenges due to their focus on integrating hundreds of scientific studies, each with non-interoperable data needing years of curation to assemble a unified assessment. Simplifying and standardizing the data collection and analysis workflows used in ecosystem assessments is required to enable regular and transparent environmental monitoring.

Regularly updated remote sensing data offer powerful opportunities to track biophysical change (figure 1(A)). Combined with AI processing methods, these data streams enable advances in mapping the extent, distribution, and even the completeness and functioning capacity (i.e. integrity) of ecosystems. For example, analyzing 89 satellite-sensed spatial data layers initiated the identification of Myanmar's threatened ecosystems under the International Union for Conservation of Nature criteria [5] and the recently launched Biodiversity Survey of the Cape integrates high-resolution hyperspectral imaging to map terrestrial and marine biodiversity and ecosystem integrity [6]. Considering the essential variables for representing biodiversity and ecosystem services [7], the Group on Earth Observations Biodiversity Observation Network has advanced thinking on how to standardize measurements, which is critical to creating replicable workflows.

Despite the advances enabled by high spatiotemporal resolution data streams and consensus building around important variables [8], key challenges remain in efficiently processing and translating novel data streams into meaningful indicators of ecosystem state and change. Cloud-based workflows in which data are accessed and analyzed on remote servers through a cloud service provider offer one way to accelerate these analyses. These workflows can reduce the need for maintaining local computing resources dedicated to downloading, storing, and processing datasets. Cloud platforms designed for storing and analyzing large archives of environmental spatial data have already been used to map and continuously monitor forests [9, 10]. As data streams evolve, platforms will need to focus on data and model interoperability so that both new and past data streams and analyses are comparable, ensuring ecosystem monitoring workflows can be repeated and compared through time.

1.2. Harmonize *in situ* and remotely sensed data

In situ data are essential to validate information obtained via remote sensing and enrich its use in supporting detection of subtle drivers of change [11]. Automating *in situ* data collection and processing whenever possible could facilitate incorporating these data into reproducible ecosystem assessments (figure 1(B)). Internet of Things networks and edge clouds (in which computational processes happen as close as possible to sensors and end-users) create a possibility to rapidly process data collected at remote locations, speeding processing by avoiding the need to transfer the data to centralized servers. For example, at the University of California's Sedgwick Reserve, computer scientists addressing the needs of conservation land managers have developed a camera-trap and edge cloud AI system that captures and classifies photographs at the reserve [12]. Technology sectors with experience implementing smart devices networks could be instrumental in adapting these technologies for ecological monitoring by collaborating with ecologists and land managers.

Synergizing ground and remotely sensed data for ecosystem assessments also generates opportunities to collaborate with local communities, incorporate their knowledge, and achieve collective benefits. Efforts in this direction include the Commonwealth Scientific and Industrial Research Organisation partnership between scientists, the private sector, and traditional landowners to protect ecosystems and cultural values from feral cattle by developing AI models that combine herd movement data (collected via Global Positioning System-tracking ear tags) with remotely sensed environmental layers [13]. Within this partnership, traditional landowners lead on-ground activities, develop ethical animal handling norms, and will ultimately benefit from novel environmental monitoring tools to manage their lands. Following the Collective Benefit, Authority to Control, Responsibility, Ethics Principles for Indigenous Data Governance [14], to avoid data inequities and exploitation, upcoming ecosystem assessments must be conducted with collaboration and deep consideration of the people who are part of those ecosystems.

Multi-scale monitoring programs, which integrate measurements and environmental surveillance across spatial, temporal, and administrative scales, have great potential to assess the integrity of ecosystems, but their design, setup, and maintenance are costly. Substantial financial support from governments, philanthropists, and other stakeholders is needed to make multi-scale monitoring part of long-term ecosystem assessments deployable across the globe.

1.3. Integrate socioeconomic and biophysical data

Future ecosystem assessments cannot ignore human dependence on nature or anthropogenic drivers of environmental change. Developing indicators of socioeconomic attributes that can be integrated into ecosystem assessments is therefore vital to improve monitoring of human-nature interactions and land and sea management practices. For example, researchers recently used high spatial resolution satellite imagery of night lights as an indicator of economic activity to quantitatively assess whether mangrove ecosystems mitigate the impact of hurricanes in Central America [15]. By comparing mangrove widths to hurricane impact on night lights, they found that robust mangrove belts greatly diminish economic damages caused by hurricanes on coastal communities. Such analyses highlight the opportunities in using remotely sensed data's increased resolution to monitor the social component of coupled human-natural systems and the possibility of incorporating ecosystem services into ecosystem assessments.

Integrating environmental remote sensing with census and household survey data has great potential to characterize human interactions with nature [16]. This data integration requires broader-scale monitoring of socioeconomic attributes to match and combine with remote sensing methods for biophysical ecosystem attributes. One such example is the merging of remotely sensed data on climate and land-cover change with the United States Agency for International Development's Demographic and Health Surveys, a global standardized instrument including hundreds of social, health, and economic variables on millions of individuals. Researchers used this combined dataset to quantify impacts of protected areas on human well-being within 34 developing countries [17]. Recent studies have also shown how social media data can help measure human access to nature [18] and its relation to mental health [19]. Incorporating socioeconomic data into ecosystem assessments could illuminate how breakdowns in human-nature interactions may signal the onset of environmental degradation processes and reveal potential vulnerabilities to maintaining quality of life.

Going forward, a coordinated effort from governments and global agencies to develop regularly updatable survey methods customizable for different regions could significantly facilitate the integration of socioeconomic information into repeatable ecosystem assessments. Collaboration among different academic disciplines and the inclusion of governmental and private sectors as crucial data providers will be needed to further such initiatives (figure 1(C)). Furthermore, similarly to sensitive biodiversity information (like endangered species surveys), privacy is an issue when working with people's data. The high spatial resolution required to form strong predictive relationships between socioeconomic characteristics and ecosystem service demand or ecosystem vulnerability may prevent making some socioeconomic datasets public.

1.4. Access to cyberinfrastructure and technical knowledge

Data preservation cyberinfrastructure and practices have progressed significantly in recent years, notably with the recognition of the FAIR principles, which advocate for Findable, Accessible, Interoperable, and Reusable digital assets [20]. However, important challenges remain in integrating various data sources and models into ecosystem assessments. Although these challenges are not specific to ecosystem assessments, they are amplified by the often multidisciplinary nature of the evaluations. Programs working towards using AI to couple data and models following our understanding of complex human-natural systems include the Artificial Intelligence for Environment & Sustainability platform [21]. Initiatives like this show how AI can make environmental modeling more accessible by creating networks that grow as scientific collaborators contribute to them.

Large cyberinfrastructures have become well-suited for analysis and continuous integration of data automatically collected by sensors due to recent advances towards standardization. For example, the development and increasing use of the SpatioTemporal Asset Catalog specification has simplified how massive geospatial data collections are found and accessed in the cloud. Assuring long-term access to private Big Data storage and analysis cyberinfrastructure or securing large-scale public investment in such platforms is required to sustainably employ them in ecosystem monitoring and deliver a greater return on investment. Moreover, as platforms to optimize ecosystem assessments evolve, standards for interoperability between them will be essential. Currently, workflows that can benefit from the varied strengths of multiple analysis platforms must overcome incompatibility challenges, including limited data flow between platforms and multiple storage standards.

To maximize the reusability of observational data for multi-scale monitoring, it is necessary to develop flexible infrastructures and application programming interfaces (communication mechanisms between clients and servers) that allow both access to Big Data repositories and integration of external data sources [22]. Such integration has been prevented, in part, by smaller field datasets frequently relying on unrelated field methods, heterogeneous data models, and variable metadata quality criteria, as resources and incentives to adopt unifying standards are often limited. Developing and encouraging the use of standardized semantics and metadata criteria across data systems and disciplines will be necessary to accelerate the data integration needed to perform multi-scale environmental monitoring.

Collaborations among environmental scientists and software developers will help ensure that ecological analysis platforms are designed to address end-users' needs. Successful community-driven advances include the Pangeo Project [23], which leverages continuous end-users' feedback and reviewed public contributions to develop open software for Big Data geoscience analytics. Ensuring technological solutions remain open-source and can be implemented on diverse computational infrastructures will make them more likely to be used and expand the creation of collaborative networks (figure 1(D)). This is exemplified by the Open Data Cube libraries, whose development has engaged tens of scientists and software developers worldwide and has helped multiple countries integrate insights from remote sensing into their national policies [24]. By expanding their coding and data analysis skills, environmental scientists can be better positioned to fully leverage advances in computing solutions to perform better ecosystem assessments.

2. Conclusion

Current ecological monitoring practices place ecosystems at risk of missing 2030 environmental targets such as the Agenda for Sustainable Development or 30 by 30 and could fail to inform progress on critical global objectives like the UN's Decade on Ecosystem Restoration. A new generation of ecosystem assessments that are rapid, reproducible, repeatable, and implementable at a range of spatial, temporal, and administrative scales is urgently needed to monitor our path towards these objectives. Transdisciplinary collaborations among computer and environmental scientists, software developers, and remote sensing experts from academic, non-profit, governmental, and private sectors will be vital to creating the new digital resources needed to monitor our rapidly changing environment. Owing to the accelerating uptake of technology, we are in a unique position to surpass current limitations of ecosystem assessments, placing society on a path where a synoptic and continuous assessment of the state and trajectory of ecosystems becomes a reality.

Data availability statement

No new data were created or analyzed in this study.

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Conflict of interest

Author Trevor Dhu is currently Microsoft's Asia Lead for Sustainability Science. The rest of the authors declare no competing interests.

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