Title: EnviroAtlas: A New Geospatial Tool to Foster Ecosystem Services Science and Resource Management

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Abstract: In this article we present EnviroAtlas, a web-based, open access tool that seeks to meet a range of needs by bringing together environmental, economic and demographic data in an ecosystem services framework. Within EnviroAtlas, there are three primary types of geospatial data: research-derived ecosystem services indicator data in their native resolution, indicator data that have been summarized to standard reporting units, and reference data. Reporting units include watershed basins across the contiguous U.S. and Census block groups throughout featured urban areas. EnviroAtlas includes both current and future drivers of change, such as land use and climate, for addressing issues of adaptation, conservation, equity, and resiliency. In addition to geospatial data, EnviroAtlas includes geospatial and statistical tools, and resources that support research, education, and decision-making. With the development of EnviroAtlas, we facilitate the practice of ecosystem services science by providing a framework to track conditions across political boundaries and assess policies and regulations. EnviroAtlas is a robust research and educational resource, with consistent, systems-oriented information to support nationally, regionally, and locally focused decisions.

Keywords: ecosystem services, geospatial, mapping, web-services

1. Introduction

The world is facing a growing set of environmental challenges; population continues to increase, expanding human use into environmentally dynamic or resource limited areas and raising pressures on local and regional ecosystems to satisfy attendant demands for nature's resources (Carpenter et al. 2009). Globally, focus has shifted from simply preserving intact resources to understanding and quantifying the societal benefits of ecosystems. Ecosystem services (ES) are broadly defined as the benefits people receive from nature (Costanza & Folke 1997; Costanza et al. 1997; Millennium Ecosystem Assessment 2005). The continued provisioning of these services in the face of increasing environmental challenges will require planning efforts that consider a suite of possible effects and strategic management of both anthropogenic and natural systems. The focus placed on market and non-market based valuation of ES has prompted a need for long-term, spatially complex study of the earth's natural capital, requiring both innovation and the integration of novel technologies (Carpenter et al. 2009).

The 2005 Millennium Ecosystem Assessment (MEA) highlighted that mainstreaming ES into policy and decision making depends on the availability of spatially explicit information about ecosystems, methods to measure and map ES, and the development of models and proxies for ES valuation (Maes et al. 2012). Even with adequate methods and models, much of this research could not have been accomplished in the previous decade because the computing ability to manipulate, map, model, and archive extensive ecological data (e.g., vegetation, land cover, and biophysical attributes) in sufficient detail was not widely available. As an emerging field of research, geospatial analysis of ES has grown substantially in the past decade (Seppelt et al. 2011). The use of advanced geospatial technologies, mainly Geographic Information Systems (GIS) and remote sensing, has enabled quantitative and qualitative spatial information on ES delivery and demand across multiple locales, scales, and time periods (Maes et al. 2012). Yet, many challenges remain, in part because ES have disparate spatial and temporal characteristics that were not routinely measured or mapped in the past. Historically, much of the environmental and socio-economic data have been collected with a well-defined focus and have not typically been aggregated across topic sectors nor integrated in ways that can provide meaningful insight into ES quantification and valuation.

Following increased efforts by scholars and practitioners to make conservation economically attractive and commonplace in decision making at all levels (Daily and Matson 2008), the US President's Council of Advisors on Science and Technology (PCAST) issued a report in 2011 detailing a plan to reverse the decline of ES. This plan included solutions to better integrate and utilize existing data and models, highlighted data and research gaps, and recommended the use of increasingly sophisticated eco-informatics tools to improve public and private decision making about ES management

(PCAST 2011). In response to this report, the White House Office of Science and Technology Policy and the National Science and Technology Council initiated the Ecoinformatics-based Open Resources and Machine Accessibility effort (EcoINFORMA). The goal of EcoINFORMA is to promote the development of informatics capabilities that can combine biophysical, ecological, socioeconomic, and health data to holistically assess adverse impacts to ES and evaluate management options (PCAST 2011). It uses an informatics infrastructure to combine data from disparate disciplines, time periods, and spatial scales and to make these data promptly available to both the public and private sectors in accessible formats with standards that permit interoperability. EcoINFORMA will enable information integration across the (bio-) geophysical spectrum, in concert with anthropogenic data such as demographics, suburbanization, and changing policies, in order to fully explore the relationships among ES and human activities.

In this article we describe EnviroAtlas, a web-based collection of tools and resources that seeks to meet a range of needs by bringing together environmental, economic and demographic data in an ecosystem services framework (for detailed organogram of EnviroAtlas see Supplemental Figure 1). EnviroAtlas (http://enviroatlas.epa.gov), developed by the United States Environmental Protection Agency (US EPA) and its partners, is a key component of EcoINFORMA. This open access geospatial tool allows users to access, view, and analyze diverse information focusing on ecosystem services and how their many benefits affect human health and well-being. Data related to ES supply, demand, and drivers of change are available for the contiguous mainland US (i.e. lower 48 US States) via interactive mapping technology that allows for viewing, manipulating, and downloading data at multiple spatial resolutions by ES and geographic area. Until recently, these types of data were available only to GIS practitioners with access to powerful computing resources. EnviroAtlas integrates ES research into the newest geospatial technologies enabling users with only an internet browser to access a wealth of spatially explicit data and analysis tools. Taken in isolation, each disciplinary field (e.g., economic, social, or ecological) can address only a limited range of management and policy related questions. Yet, when multiple disciplinary fields are linked together through an easy-to-use interface, the result is a novel tool that has the potential to enable better decision making across multiple sectors.

For brevity and to reach a broad interdisciplinary audience, we forego the technical details of specific datasets and models included within EnviroAtlas. Documentation and metadata for each of the more than 300 indicators are available on the EnviroAtlas website. We focus here on the general approach, data types, and analysis tools available through EnviroAtlas for the identification of ES supply and demand, index construction, drivers of change, and applications for resource management.

2. EnviroAtlas Approach

The geospatial nature of ES is well suited to the multi-indicator, systems approach used in EnviroAtlas. Due to their complexity, ES typically cannot be assessed at a single point, as they may be influenced by surrounding and distant patterns of land use, biophysical attributes, and demand. An ES framework necessitates the integration of data on ecology, demographics, economics, and public health and wellbeing. The implementation of this type of framework relies on a systems approach for evaluating how human and natural ecosystems influence and interact with each other (Richmond 1997; Maani and Maharaj 2004). By incorporating systems science into our assessment, we are able to evaluate local community information within the context of the surrounding environment.

EnviroAtlas uses indicators and indices to quantify and map ES across the contiguous United States and at finer resolution for individual communities. Indicators are selected and developed based on how well the information will contribute to the understanding of the provision of a specific ecosystem service (Barber 1994, Jackson et al. 2000). Once selected, these indicators are derived from existing, consistent, national and local data. Independently, many of the indicators do not quantify an ecosystem service, but are instead pieces of the underlying structure needed to make inferences about maintaining and sustaining the natural and human environment. Combining the selected indicators statistically into indices provides a more complete picture of a particular ES and allows for feedback loops among benefits, stressors, and drivers of change (Burkhard et al. 2012). With these indices, EnviroAtlas users can assign weights to constituent indicators to meet their own needs and criteria.

Emerging open access ES mapping tools are being applied more widely to research and decision making. The number of decision support tools specifically focused on ecosystem services has grown substantially with the increased interest in ecosystem services, though the applicability of these tools for widespread use varies (Bagstad et al. 2013). Two often used tools include InVEST (Kareiva et al. 2011), the Integrated Tool to Value Ecosystem Services and ARIES (Villa et al. 2009), Artificial Intelligence for Ecosystem Services (Vigerstol and Aukema 2011, Crossman et al. 2013). These tools have made great strides towards mapping ecosystem services across broad geographic areas. However, both tools require users to input their own data and coefficients which require a certain level of expertise. The geospatial nature of the EnviroAtlas interactive mapping application complements the more expertise driven tools by providing easy to use indicator screening, evaluation and analysis capabilities through a user friendly online platform. In addition to a range of ES data visualization and analysis tools, the

EnviroAtlas provides users the ability to download data for use in other ES tools, such as InVEST and ARIES.

3. Data organization

EnviroAtlas users range from highly skilled researchers to concerned community members. To reduce difficulty in assessing and comparing overall ES value, benefits and tradeoffs, EnviroAtlas data are organized within the mapping application into the following general benefit categories:

- Clean Air
- Clean and Plentiful Water
- Natural Hazard Mitigation
- Climate Stabilization
- Recreation, Culture and Aesthetics
- Food, Fuel and Materials
- Biodiversity Conservation

These seven *benefit categories* were selected largely because they provide a logical approach for organizing hundreds of data layers in a way that reduces redundancy while still allowing the user to understand the interconnected nature of ES. The seven benefit categories are further subdivided into finer categories based on ES supply, demand, and drivers of change. The advantage of establishing these categories as opposed to employing an existing ES classification system is that they provide flexibility for multiple uses, including education about ES. Within its organizational structure, EnviroAtlas does not distinguish intermediate (e.g. nutrient cycling, net primary production) and final ES (e.g. crop yields), as many classification systems do. While this distinction is important when incorporating ES into economic accounting frameworks, EnviroAtlas is not strictly an ES accounting tool. A number of classification systems are available or under development (e.g., MEA 2005, Final Ecosystem Goods and Services Classification System (FEGS-CS) (Landers and Nahlik 2013), The Economics of Ecosystems and Biodiversity (TEEB 2010), Common International Classification of Ecosystem Services (CICES), and System of Environmental-Economic Accounting (SEEA). While these classification systems work well in conceptual and accounting frameworks, they do not provide an ideal framework within which to organize large amounts of geospatial data. Users can crosswalk EnviroAtlas data with any conceptual framework to meet their specific needs.

A goal of EnviroAtlas is to provide data that can be used for both local and large-scale analyses. The selected organizational structure brings benefits to human health and well-being to the forefront, enabling users to instantly make those connections, regardless of the data being viewed. To demonstrate the multiple facets of ES, EnviroAtlas not only includes data on the natural resources (e.g., tree cover) that provide these benefits (e.g., clean water), but also on potential stressors or drivers of change (e.g., impervious surfaces). All of the indicators presented in EnviroAtlas can be placed readily into multiple classification frameworks. ES indicators in EnviroAtlas are included in every benefit category that is applicable, and while this leads to multiple locations of the same indicator, it also demonstrates the interdependencies among the various benefit categories and other ES. The MEA (2005) highlighted the importance of demonstrating the interdependencies among ecosystem services, and EnviroAtlas maintains this concept.

4. EnviroAtlas data and information

Within EnviroAtlas, there are three primary types of geospatial data: ES indicator data that have been summarized to standard reporting units, ES data in their native, derived resolutions, and reference data (e.g., landcover data, demographics) that help place the ES data into context. The indicators data have been developed by US EPA scientists and contractors, federal partners, and collaborators from universities and not-for-profit environmental organizations. Some of these indicators are derived from original research, whereas others are simple summations of existing data (e.g., percentages of area by landcover type). These data were created to address specific resources, demand for resources, and drivers of change. Summarizing the data to standard units allows for comparisons within and across the nation, regions and local communities. For a complete list of ES indicators included in the EnviroAtlas see Supplemental Figure 2.

4.1 Nationwide ecosystem services indicators

EnviroAtlas nationwide research uses the National Land Cover Database (NLCD, www.mrlc.gov), a 30 meter resolution product developed by the Multi-Resolution Land Characteristics Consortium (MRLC) every five years. Other data sets frequently used for the national assessment include the National Hydrography Data (NHD), Soil Survey Geographic Database (SSURGO,) and State Soil Geographic Database (STATSGO), US Census Bureau demographics, and ESRI Business Analyst.

The US Geological Survey, in collaboration with US State agencies and other organizations, has subdivided the contiguous US into nested hydrologic accounting units (HUCs) ranging in extent from multi-state regions (HUC-2s) to sub-county basins (HUC-12s) (Seaber et al. 1987). EnviroAtlas has adopted the HUC-12 scale, featuring more than 90,000 similarly sized spatial units across the contiguous US for summarizing ES indicators. The collection of national ES information into these accounting units allows for statistically rigorous index creation and indicator comparisons across large geospatial areas.

Nationally consistent ES data provide: 1) a framework to assess existing national policies and regulations, 2) the means to track conditions across political boundaries, 3) a robust research and educational resource, and 4) consistent information to support nationally, regionally, and locally focused decisions. While some of the national indicators are based on simple aggregations of foundational data such as the NLCD, many others are the products of extensive research aimed at providing indicators of ES supply, demand, and drivers of change. To date, more than 150 national indicators have been developed for EnviroAtlas (Figure 1). For illustrative purposes, a small subset of these national indicators, including terrestrial biodiversity conservation (supply), water consumption (demand), and nitrogen loads (driver of change), are described in more detail below.

Vertebrate species richness indicators can be representative of available resources, recreational opportunities, culturally important resources, rarity, or aesthetic qualities. Indicators related to game species highlight wild food and recreational opportunities available within an area, while total species habitat has been used as an indicator of conservation potential and biodiversity. The modeled species richness biodiversity indicators developed for EnviroAtlas are based on data generated by the US Geological Survey (USGS) National Gap Analysis Program (GAP; Boykin et al. 2013). GAP maps the distribution of natural vegetation and potential suitable habitat for individual terrestrial vertebrate species. Therefore, these indicators are based on habitat models while other indicators in EnviroAtlas are based on species observation data. For these modeled data, potential habitat may be specific to wintering, breeding, or year-round activities depending on the species. When used in conjunction with other maps in EnviroAtlas, biodiversity indicators can help identify areas with high ecological or recreational value that may be under pressure from nearby urban or infrastructure development, or where additional land protection efforts could further enhance habitat potential for specific terrestrial species.

Individuals and communities depend on water resources for drinking (Mehaffey et al. 2005), household use, recreation, agriculture, industry, power generation, and transportation. Evaluating this type of demand can provide insight into the delicate balance between water availability and use across the US. EnviroAtlas currently provides four indicators of water demand: domestic, agricultural, industrial, and thermoelectric. Domestic water demand includes all indoor and outdoor uses, such as for drinking, bathing, cleaning, landscaping, and pools for primary residences. Industrial water demand includes water used for manufacturing and production of commodities, including chemical, food, paper, wood, and metal production, while thermoelectric water demand includes the amount of water used by coal, oil, gas, and nuclear plants for the generation of energy. Agricultural water demand is the total volume of water used for irrigation, and includes water used before, during, and after growing seasons to suppress dust, prepare fields, apply chemicals, control weeds, remove salt from root zones, protect crops from frost and heat, as well as other activities needed for harvesting. Each of the water demand indicators resolves USGS county-level water use data to the HUC12 watershed basins using finer-scaled data such as the NLCD land use and cover, downscaled census population data, and facility locations. The four water use metrics can be used individually or together to evaluate which sector requires the greatest water resources, or in conjunction with other maps such as riparian forests to highlight where ecosystems that help protect water resources may experience strain, require protection, or benefit from restoration.

The active nitrogen compounds in the atmosphere and biosphere, called reactive nitrogen, can act as a driver of change for a number of ES. For example, it can positively enhance crop production while causing negative impacts on water quality through eutrophication (Compton et al. 2011, Jones et al. 2014). As a way to evaluate the type and volume of nitrogen input, EnviroAtlas provides measures of the quantity of synthetic and organic nitrogen fertilizer applied to farmlands, and measures of nitrogen inputs to the ecosystem through cultivated and natural nitrogen fixation (Figure 2). Synthetic and manure fertilizer applications were estimated from county-level inputs; these data were downscaled to 30m resolution based on crop type, and re-aggregated to the HUC12 watershed unit. Biological nitrogen fixation was modeled as a function of total acres of leguminous crops and natural ecosystem (Sobota et al. 2013). Estimates of nitrogen from atmospheric deposition as well as point sources are also included. These indicators can be used alone or in conjunction with other data layers to help identify areas where nitrogen is a significant pollutant source, or in models that examine the transport and cycling of nitrogen across terrestrial and aquatic ecosystems. They can also play a role in providing information needed for the development of nutrient reduction strategies, nutrient credit exchanges, and payments for ES.

4.2 Community ecosystem services indicators

Cities, towns, and Tribes represent concentrated demand for ecosystem goods and services. Most ecosystem benefits aggregate to populated places, where residents may depend on natural products and services provided by mechanisms that originate from local to global environments. The community component of EnviroAtlas provides information about the magnitude and distribution of services from local, natural infrastructure. It includes indicators of the built environment, which factors into the accessibility and utility of local environmental assets. Census demographic data allow for the assessment of disproportionate vulnerability and need across groups. The community component includes information about the critical role that the local natural environment plays in physical and mental well-being by buffering hazards and facilitating healthy habits. The extent and distribution of trees, grass, water, and other landcover types provide the foundation for community ES indicators. Numerous additional geospatial datasets, including road networks, school sites, and downscaled population data, also contribute to the development of EnviroAtlas community indicators. There are almost 100 community ES indicators in the initial release (Figure 1).

Since resources are not available to characterize all US communities at a fine resolution, EnviroAtlas features a strategic selection. Communities are chosen based on geographic, environmental and demographic gradients, gradients in health and environmental rankings as determined by government and private initiatives, the availability of complementary data (e.g., public health, environmental) that are consistent across multiple communities, local capacity for participatory research, and the ability to leverage ongoing projects. Communities included in the initial public release of EnviroAtlas are Durham, NC; Portland, ME; Tampa, FL; Phoenix, AZ; Pittsburgh, PA; and Milwaukee, WI. Additional communities planned for inclusion by the end of 2014 include Austin, TX; Salt Lake City, UT; Paterson, NJ; Green Bay, WI; Woodbine, IA; Portland, OR; Fresno, CA; Memphis, TN; and New Bedford, MA. Communities will be added annually to reach fifty by 2017.

EnviroAtlas community-scale research uses aerial photography from USDA's National Agricultural Imagery Program (circa 2010), supported by LiDAR and other data, to create 1-meter resolution landcover data with nine classes: impervious surface, trees and forest, shrubs, grass and herbaceous, water, soil and barren, agriculture, and wetlands (woody and emergent). Community-level indicators in EnviroAtlas draw from the 1-meter land cover data, census data, local infrastructure data, and environmental and health models. EnviroAtlas indicators are consistent across featured communities and are summarized at the census block-group scale. A block group is a US Census geographic unit, nested between the block and tract units. Block groups typically contain between 600 and 3,000 people and differ widely in spatial extent due to their delineation by population density. The block group is the smallest unit for which the Census provides median household income and other socioeconomic variables from sample data.

EnviroAtlas boundaries for each community listed, except Durham, NC, are derived from 2010 US Census Urban Area boundaries. As these are based on census blocks rather than block groups, EnviroAtlas communities include all block groups with more than 50 percent of their populations, as determined by downscaled population grids, falling within the Census Urban Area. Depending on the community, boundaries may be clipped at county lines to exclude some remote areas. Occasionally, block groups may be added to address a critical population. For example, several block groups were added to the greater Phoenix area to include adjacent tribal lands.

The community component features a large suite of indicators provided by the USDA Forest Service and collaborators using the *i-Tree* toolkit (USDA Forest Service 2008). *i-Tree* combines EnviroAtlas high-resolution landcover data for each featured community with local environmental data from US EPA air monitors, USGS gauging stations, and other sources. US EPA air modeling data and national averages for stream pollutant concentrations are also used. These data populate *i-Tree* models that estimate the extent to which local tree cover reduces annual air and water pollution, stormwater runoff, and ambient summer temperatures. Additional *i-Tree* indicators in EnviroAtlas include above- and below-ground carbon sequestration and storage by tree cover, the value of this sequestration and storage in US dollars based on carbon market prices in 2010 (Nowak et al. 2013a), and dollar values for reductions in carbon monoxide and airborne particles between 2.5 and 10 ug.

EnviroAtlas also includes quantitative estimates of selected population health benefits and their economic value from estimated reductions in carbon dioxide, sulfur dioxide, nitrogen dioxide, and fine particles (<2.5 ug) by local tree cover. The Forest Service uses US EPA's BenMAP tool (www.epa.gov/benmap) to calculate these values from its *i-Tree* estimates and local population data (Nowak et al. 2013b). BenMAP models of health impacts derive from meta-analyses of the scientific literature. Therefore, they may not apply to specific block-group populations that differ from the original study participants in socioeconomic status, baseline health status, health behaviors, or contributing environmental risks (Hubbell et al. 2009). Calculations for EnviroAtlas communities do account for local population size and age distribution; they also reflect local air monitoring data used in the *i-Tree* estimates.

In addition, EPA scientists have developed a suite of maps involving population proximity to green infrastructure as indicators of hazard buffering and opportunities for recreation, social engagement, and cognitive restoration. Like the BenMAP health indicators, these are based on scientific literature; they also integrate population data with environmental measures. Some examples of community maps based on emerging research include the following: residents beyond 500 meters from a park entrance, residents with minimal views of trees, and residents within 300 meters of a major road that lacks tree cover along the roadside. Figure 3 provides an example of the types of data that can be viewed within the interactive mapping application. The health implications of these maps include obesity and depression due to reduced opportunity for physical activity (e.g., Peacock et al. 2007, Wolch et al. 2011); stress and reduced cognitive function due to lack of visual access to green space (e.g., Tennessen and Cimprich 1995, Hartig et al. 2003); and asthma exacerbation from vehicular pollution (HEI 2010). Further exploration of disproportionately vulnerable populations is possible by overlaying demographic data for percent children, seniors, and minority and low-income residents per block group (Figure 3).

4.3 Additional data

So that users may better understand and evaluate ES, ancillary data are included in EnviroAtlas under *People and Built Spaces* and *Supplemental Maps*. These additional data provide valuable information about those who benefit from ES, built infrastructure that may aid or hinder their use, and biophysical features important for context. Due to their file size and lack of conformity with EnviroAtlas spatial accounting units, some ancillary data as well as ES indicators are included in *Supplemental Maps*.

People and Built Spaces includes demographic data derived from the 2006-2010 American Community Survey (ACS) and the 2010 census. They are provided at the census tract for the nation and at the census block group for each featured community. Additionally, urban design indicators are included from the US EPA's Smart Location Database, a geographic data resource that includes more than 90 indicators for estimating housing location efficiency at the census block group scale. Indicators on employment, housing, land use diversity, intersection density, and access to jobs and workers are provided within EnviroAtlas.

Supplemental Maps are organized into four sections: 1) boundaries, 2) US EPA waters data, 3) biophysical vector data, and 4) biophysical raster data. Boundaries include the physical demarcations for each EnviroAtlas community, each HUC-12 watershed, political areas, and ecological regions. The US EPA waters data are summarized maps that contain information for US EPA reported impaired and assessed (303d) waters in 2010. These data were obtained from state reported assessments of the condition of their water bodies. Each state is required under the Clean Water Act to report these assessments directly to Congress every two years. Biophysical vector data include the National Hydrography dataset, habitat connectivity data, GAP ecological systems, soils data, and data from the National Wetlands Inventory. The biophysical raster data provide one-meter resolution land cover for EnviroAtlas featured communities, the downscaled population grid, and 30-meter resolution datasets of rare ecosystems and potentially restorable wetlands.

5. Analysis tools and downloadable toolkits

In addition to geospatial data, EnviroAtlas includes tools and resources that support research, education, and decision-making. The Eco-Health Relationship Browser is an interactive graphical viewer for exploring published linkages between ES and numerous public health issues (Jackson et al. 2013). Tools such as Watershed Navigator and Raindrop are embedded within the interactive map and are designed for use with EnviroAtlas data. The Watershed Navigator allows users to select any location and navigate upstream or downstream from that point by travel time or distance within the stream network. The Raindrop tool allows users to select any location on the map and determine the general flow path and distance to the nearest water feature that is down gradient.

Downloadable geospatial tools, such as the Ecosystem Rarity Toolbox, the Analytical Tools Interface for Landscape Assessments (ATtILA), the Intelligent Dasymetric Mapping (IDM) toolbox, and the Automated Geospatial Watershed Assessment (AGWA), are also provided in EnviroAtlas. The Ecosystem Rarity Toolbox allows users to calculate the relative rarity of individual ecosystems at multiple scales for specific areas of interest. The IDM assists in preparing requisite vector and raster datasets for population mapping from census data, and performs the calculations to generate the downscaled population density grid. ATtILA is a toolbox that calculates many commonly used landscape, riparian, stressor, and other indicators used in ecosystem assessments. The AGWA tool parameterizes and automates the running of the Soil Water Assessment Tool (SWAT) and KINematic Runoff and EROSion (KINEROS2) hydrologic models, and allows for spatial visualization of the results.

6. Indices for ecosystem services evaluation

One EnviroAtlas goal is to provide users with the ability to statistically combine indicators into indices that can be used to evaluate current and future ES across an area of interest (community, state, region or nation). Within the EnviroAtlas mapping application, users can select prepared indices or use provided analytic tools to develop their own. The analytic tools included in the mapping application are based on work previously conducted under US EPA’s Regional Vulnerability Assessment (ReVA) Program (Smith et al., 2003).

These analytic tools allow a user to choose among three complementary statistical methods: 1) Simple Sum for examining current and future overall spatial patterns of environmental quality, 2) Stressor-Resource overlay for estimating vulnerability (Smith et al., 2003; Jackson et al. 2004), and 3) generalized weighted Euclidean Distance statistical technique (Tran-D) for grouping units of like condition (Tran et al., 2006). The Simple Sum method was selected for initial implementation because it is easily understood and communicated. The Stressor-Resource Overlay method was included for its ease of interpretation and the ability to map levels of vulnerability. Spatial reporting units with extensive resources and multiple stressors are considered the most vulnerable to ES loss.

The Tran-D statistical technique is perhaps the most robust of the statistical methods included in EnviroAtlas. This generalized distance measure groups units with similar ES quality allowing for a comprehensive assessment that includes data on benefits, stressors, and drivers of change.

All data manipulated with these analytic tools are normalized, and inverted if representing a stressor, with values ranging from 0 (most beneficial for an ecosystem service) to 1 (least beneficial). Multiple indicators can be combined into a single index value for display in the EnviroAtlas visualization and graphing tools. Currently, EnviroAtlas uses Fusion Chart Suite XT (v3.3.1) to provide spider diagrams (Figure 4), box plots and tables for a set of prepared ES indices generated by Simple Sum statistics with pre-set weights found in the ES Analyzer tool. Users can also build indices by selecting their own sets of indicators and weights. All of the indicators used in the ES Analyzer have been examined for statistical interdependencies with a variance-covariance matrix. Indicators with unusually high correlations (>0.95) were examined for possible inappropriate redundancy and dependency. Where redundancy or dependency was found one of the indicators was eliminated from the Simple Sum. By the end of 2015, a widget will be included in the EnviroAtlas mapping application that will allow users to build ES indices using the more sophisticated Stressor-Resource overlay and Tran-D statistical methods. While user guides are provided for the index tools users should have some understanding of the ecosystem services and basic statistics in order to build appropriate measures and interpret the resulting maps.

7. Forecasting ecosystem services using future scenarios

Understanding the dynamic nature of human and environmental systems is important for understanding the future effects and consequences of policy and planning measures (Burkhard et al. 2013). Presently, EnviroAtlas provides information on current ecosystem goods and services; however, a priority is to develop and integrate future climate, population, and landcover scenarios to forecast ES. EnviroAtlas is using the FOREcasting SCEnarios of land-cover (FORE-SCE) data developed by the USGS EROS Center (Sohl et. al. 2007) to calculate indicators related to future land cover and use under two distinct emission scenarios and three future time periods (2030, 2060, and 2100). The first landcover scenario is based on rapid growth and the second is developed around local environmental sustainability. Land cover and land use data can then be paired with future climate scenario information included in EnviroAtlas for evaluation of possible effects to specific ES related to potential future changes.

In 2014, the Intergovernmental Panel on Climate Change (IPCC) released its most recent future climate modeling efforts, the Representation Concentration Pathways (RCPs) process. Each RCP makes certain assumptions about future land-use and energy development, population growth, and other socio-economic factors which help to drive the emission scenario. These future scenarios describe plausible trajectories of different aspects of possible future climates and serve as a common method for evaluating global change science. Three of the RCPs (RCP 4.5, 6.0, and 8.5) for the years 2010 to 2100, inclusive, will be included within the interactive mapping application of EnviroAtlas. Future scenario information within EnviroAtlas is based on the high resolution (800 meter) DCP30 downscaled climate projections, which were developed by the NASA Earth Exchange scientific collaboration platform (Taylor et al. 2012). RCP probabilistic future emission scenarios can be cumbersome and difficult to incorporate into ES analyses due to the complexity and sheer volume of data. However, EnviroAtlas provides the platform to house a newly developed widget tool to easily disseminate these data (Pickard et al. 2015). By providing the RCP 4.5, 6.0, and 8.5 scenarios within this widget, users can access information on potential forecasted climate change effects in conjunction with the ability to compare current and future ES.

In addition to future scenarios, EnviroAtlas also summarizes modeled historical climate data (PRISM, Daly et al. 1997) from 1901 to the present (2010). Therefore, users have scrollable, map-based access to climate data and information that range from 1901 to 2100 and are summarized for each HUC-12 watershed within the contiguous US. The inclusion of historical climate data is to allow for comparisons of future scenarios to user defined baselines. By providing this information for approximately 200 years, users can have the power to establish their own historical, current, or future baselines and make comparisons. The first version of the future scenarios tool will be limited to a few climate variables (temperature, precipitation and evapotranspiration); however, the potential exists to include any indicator that has both spatial and temporal dimensions. Further incorporation of modeled future and retrospective data will move EnviroAtlas beyond a fixed point in time and ultimately increase the utility of ES interpolation and valuation.

8. Discussion

There is an increasingly urgent need for tools that help incorporate ES into planning, policy, and decision making (de Groot et al. 2010, Maes et al. 2012, Crossman et al. 2013, Burkhard et al. 2013, PCAST 2011). However, advancing the ES approach requires developing novel methods to estimate ES benefits derived from ecosystems across multiple scales (Posthumus et al. 2010). Mainstreaming ES into policy and decision making is dependent on the availability of spatially explicit information on the state and trends of ecosystems and their services (MEA 2005, Maes et al. 2012). This information must be of a resolution adequate to meet the requirements of a particular decision and communicated in a way that makes the data accessible to a wide range of users. Despite recent efforts in developing models to support ES decision making, there remains a need for available ES data that does not over burden the user with substantial resources, time, and effort (Bagstad et al. 2013). EnviroAtlas was initiated by the EPA to make ES data and tools easily accessible to the public.

EnviroAtlas provides a publicly available decision support tool centered on ecosystem services that is straight forward and contains a wealth of ES indicators and related data in one place. While the spatial extent of EnviroAtlas is currently the contiguous US, data are provided at a fine enough resolution that it can inform local to national decisions. EnviroAtlas also includes indicators that can be used to inform market valuation, which translates ES into terms that that may be more readily understood by decision makers and the general public (National Research Council 2004). Some of these indicators include ecosystem condition, public health estimates, societal preferences, and intrinsic value.

The use of land cover and land use in combination with additional qualitative and quantitative data has become a commonly used method to assess ecosystem service provisioning (Burkhard et al. 2009, Burkhard et al. 2012, Crossman et al. 2013). EnviroAtlas has improved this approach by combining land cover/land use data with many other biophysical and socio-economic data to derive innovative indicators that can be aggregated into index values. The ES assessment framework within EnviroAtlas contains three key elements: 1) the use of standardized spatial reporting units that allow for the calculation of index values and the investigation of multiple ecosystem goods and services across those reporting units; 2) the ability to aggregate individual indicators into indices; and 3) methods to value individual elements within indices.

EnviroAtlas not only imparts a basic visualization of ES indicators, but also allows users to evaluate multiple ES simultaneously using its analysis tools. Thus, users can more easily identify the synergies and tradeoffs among these ES, where simply providing a mapping application would not meet this need (Pagella and Sinclair 2014). EnviroAtlas data can be downloaded or accessed through web services for users who wish to conduct analyses using an alternative ES tool. Providing consistent data aggregated to a standard reporting unit also facilitates the valuation of ecosystem services. Though designed within an ES framework that encourages and promotes a systems approach to decision making, potential uses for EnviroAtlas are not limited to ES assessments as nationally consistent data can be used for multiple purposes.

Locally observed ES issues are often best resolved from regional or landscape perspectives (Musacchio 2009) and can require multi-scaled data. EnviroAtlas provides the ability to evaluate and integrate ES information at multiple scales. For example, EnviroAtlas provides stream reach level and summarized information on 303d impaired waters throughout the contiguous US. While 303d waters can be impaired from numerous stressors, communities can craft localized solutions that are tailored to their individual needs, such as reducing nitrogen fertilizer input in critical areas. Using EnviroAtlas, communities can not only craft these local solutions to benefit water quality, but can easily evaluate the full suite of ES benefits in relation to water quality. The ability to relate ES analyses at a macro scale to resolutions that affect individual communities allows EnviroAtlas users to recognize the direct relationship between the environment and human well-being.

The success of EnviroAtlas is tied to the continued availability of nationally consistent foundational data, as subsequent EnviroAtlas releases will be based on the most current data available. Without regular updates to the National Land Cover Data, cropland data layers, Census data, and many others, EnviroAtlas would be unable to remain current and maintain relevancy for users. In its first iteration, EnviroAtlas provides consistent data for the contiguous US only, given that much of the fundamental foundational data for Alaska and Hawaii have not been developed. By providing consistent data over time, EnviroAtlas will develop the capacity for trends analysis. In addition to current trends the EnviroAtlas will allow users to combine ecosystem service data with future landcover and climatic drivers of change for both the immediate (e.g. 2025) and distant future (e.g. 2080). These types of information will be increasingly important for addressing issues of adaptation, conservation and resiliency. For example, understanding the location and distribution of climate vulnerable cash crops such as fruits and vegetables in relation to potential areas of future drought will be important for land managers and the agricultural sector.

One of the main goals for the development of the EnviroAtlas public web tool is to reach a broad audience, including those involved in education, conservation, land management and policy, as well as scientists. Prior to its public release in May 2014, EnviroAtlas underwent a peer review and beta-test with over 600 participants to ensure that the tools and resources provided were appropriate for a broad user base. Feedback obtained from both of these reviews was incorporated into EnviroAtlas when feasible. Between May 1 and December 31, 2014, web site use tracking using Google Analytics indicates there were approximately 25,000 web sessions on the EnviroAtlas web site, of these 33% returned to the site multiple times. Of the 25,000 sessions, at least 11,600 used the interactive map. Over 152,000 map views occurred within these 11,600 sessions. A map view occurs when a user turns on a data layer or uses one of the tools. Based on these early results, pre-release testing (Figure 5), and reported examples from users, it appears that EnviroAtlas is reaching a broad audience and being heavily used.

EnviroAtlas tools and data have already been used in a diverse range of projects. At the national scale, the Fish and Wildlife Service is investigating the use of EnviroAtlas maps on threatened and endangered species and GAP Ecological Systems to prioritize lands for conservation. EPA's Office of Water is using many of the EnviroAtlas data layers to help inform decisions regarding prioritizing watershed to address water quality impairment issues based on their recovery potential. In Wisconsin, EnviroAtlas dasymetric maps, which use techniques to allocate the population based on the habitability of lands, were used to help identify areas for placement of new cell phone towers.

In Durham, NC, EPA scientists, in collaboration with Trees Across Durham, used EnviroAtlas community data to prioritize efforts for a wide-scale tree planting project. The project took place in 2013 (using the beta version of EnviroAtlas) with Durham city planners identifying 19 elementary schools across the city that best fit their ES values and needs. They planted nearly 300 trees, with the identification of additional sites for tree planting in the future. Additionally, the Southeast Atlantic Landscape Conservation Cooperative is incorporating EnviroAtlas layers as web services in its Conservation Blueprint that is currently under development. The Eco-Health Relationship Browser was used by the Cincinnati Health Department in staff training on Health Impact Assessments and was also featured during the keynote address at the 2014 International Congress of Positive and Coaching Psychologists to illustrate the benefits of simple nature interventions. Universities are using EnviroAtlas in the classroom; by request, we are currently developing education curricula that will be available on the website. Since users do not have to request access to use EnviroAtlas, it is likely that there are other examples of projects that are using EnviroAtlas of which we are unaware. The examples reported here were largely discovered after the fact and were unsolicited by EPA.

EnviroAtlas is a living product with on-going efforts continuing towards developing a more complete suite of indicators and tools to quantify ES across the US. In addition to incorporating new data, EnviroAtlas functionality will be kept up to date to meet user needs, including making the interactive tools mobile-friendly for use on smart phones and tablets. The majority of the EnviroAtlas indicators rely on land cover data. Therefore, major updates to the national indicators will coincide with new releases of NLCD and additional cities will use more recent NAIP imagery for indicator development as it becomes available. The collaborative nature of EnviroAtlas encourages further integration through the development of partnerships with multiple federal and non-federal entities that are able to contribute to its development. One priority area for EnviroAtlas in the coming years is to develop a more robust set of indicators aimed at quantifying the socioeconomic benefits that people receive from their environment, including human health. The continued development of original research, indicators, and community data for EnviroAtlas will serve to further strengthen our ability to reach a diverse audience about the wide range of benefits we receive from ecosystem services.

9.0 Acknowledgements

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Figures:

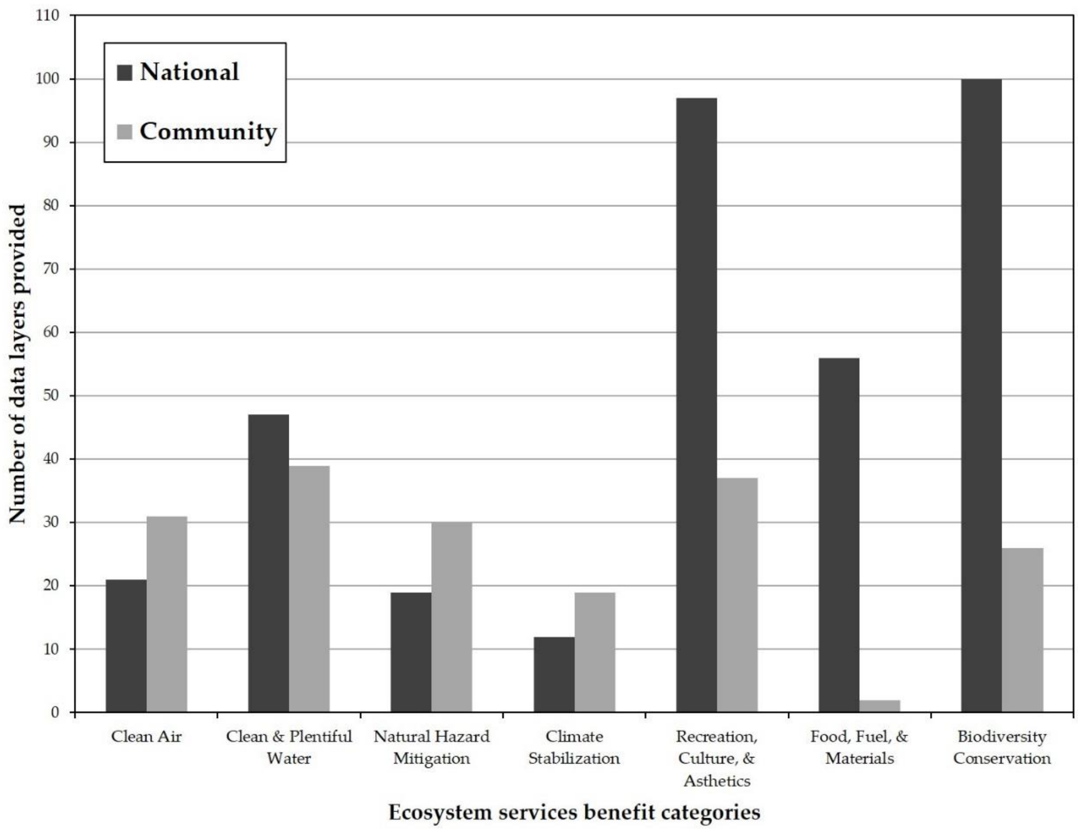

Figure 1. Number of ecosystem service indicators provided in EnviroAtlas. There are seven ecosystem service benefit categories that are used to categorize indicators within EnviroAtlas.

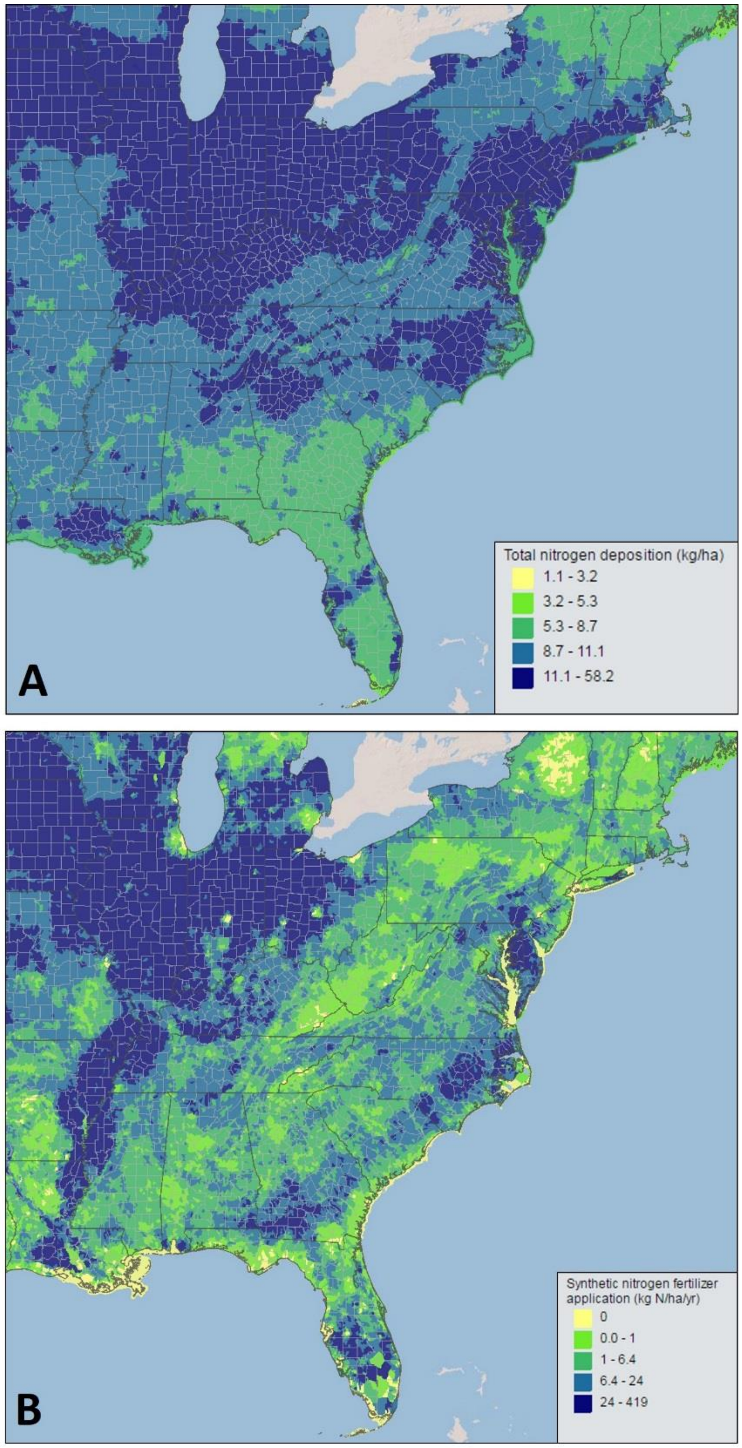

Figure 2. EnviroAtlas interactive map showing the total nitrogen deposition (kg/ha) (A) and the synthetic nitrogen fertilizer application (kg N/ha/yr) (B) for each HUC-12 for the east coast of the US.

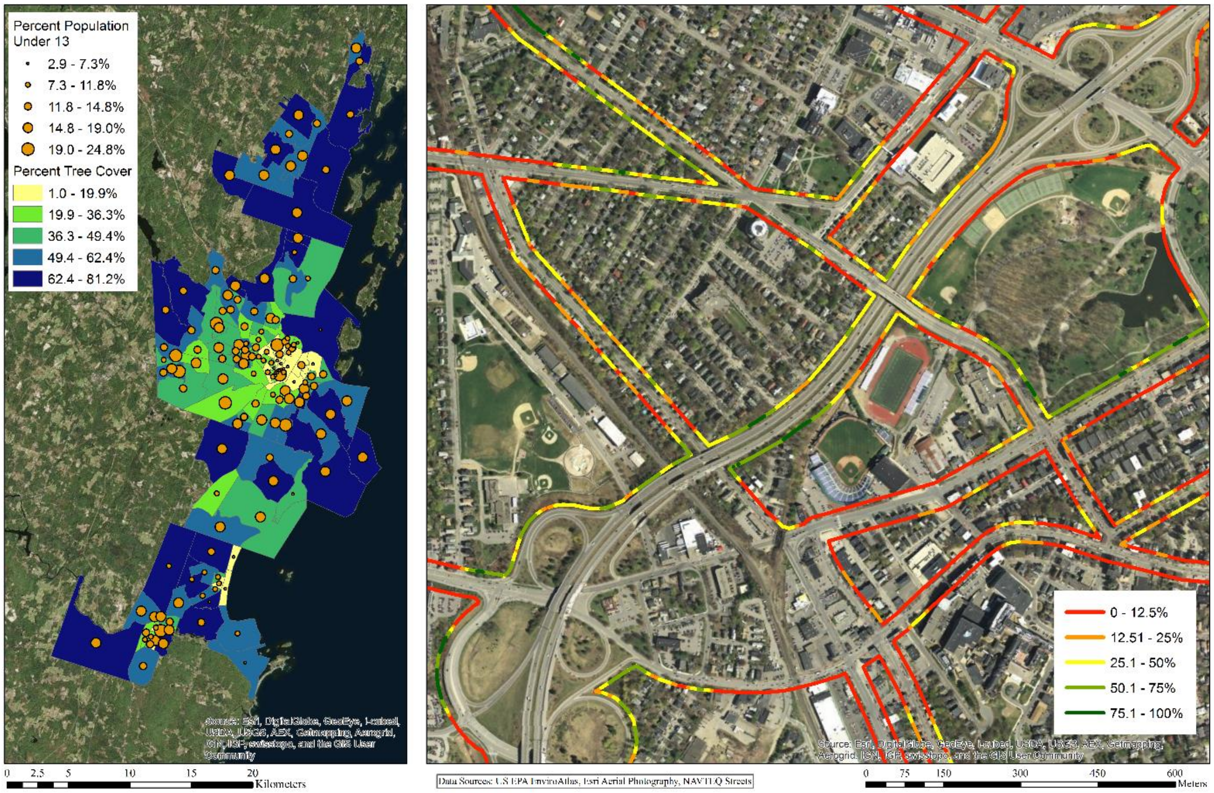

Figure 3. Examples of community maps within EnviroAtlas for the city of Portland, Maine showing the percent of the population under 13 overlaid on top of the percent of tree cover within each census block group (A) and the percent of tree cover within 26 meters.

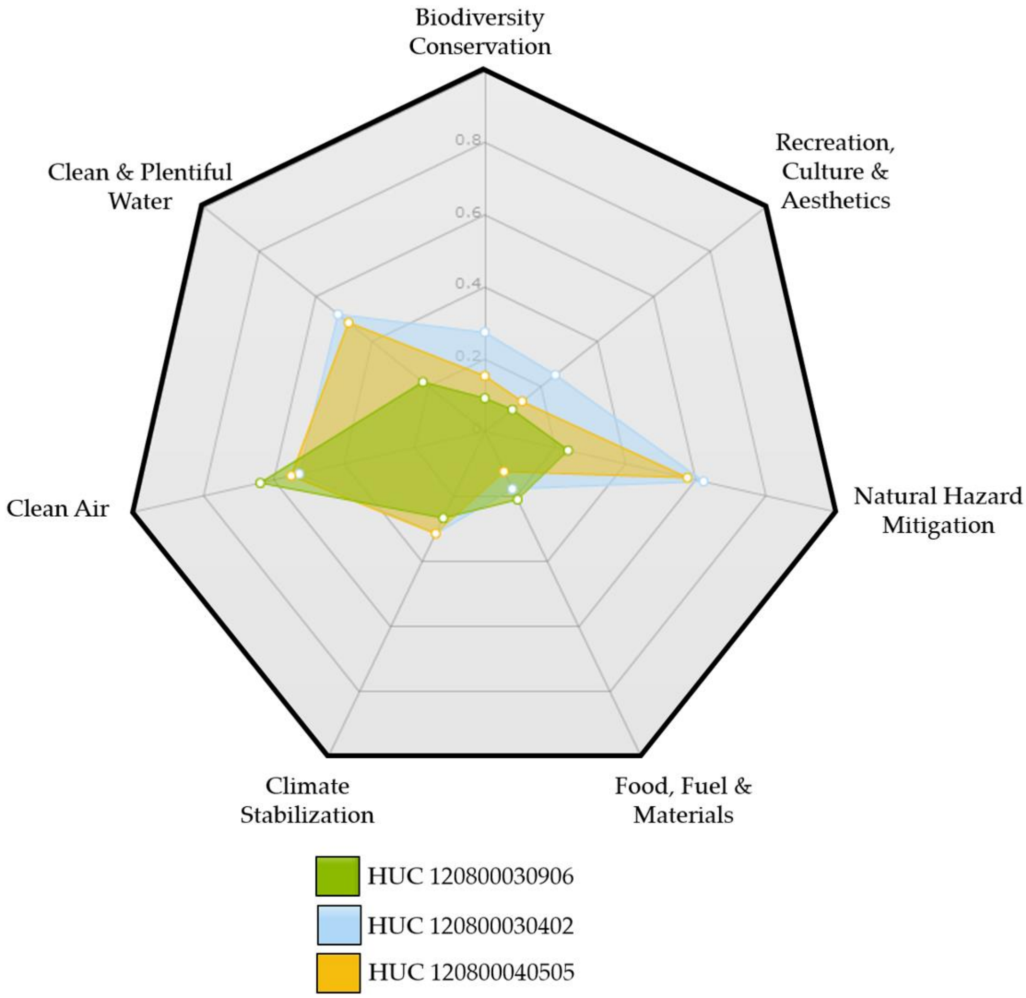

Figure 4. Example spider diagram output from the Ecosystem Services Analyzer Tool for three HUC-12 watersheds.

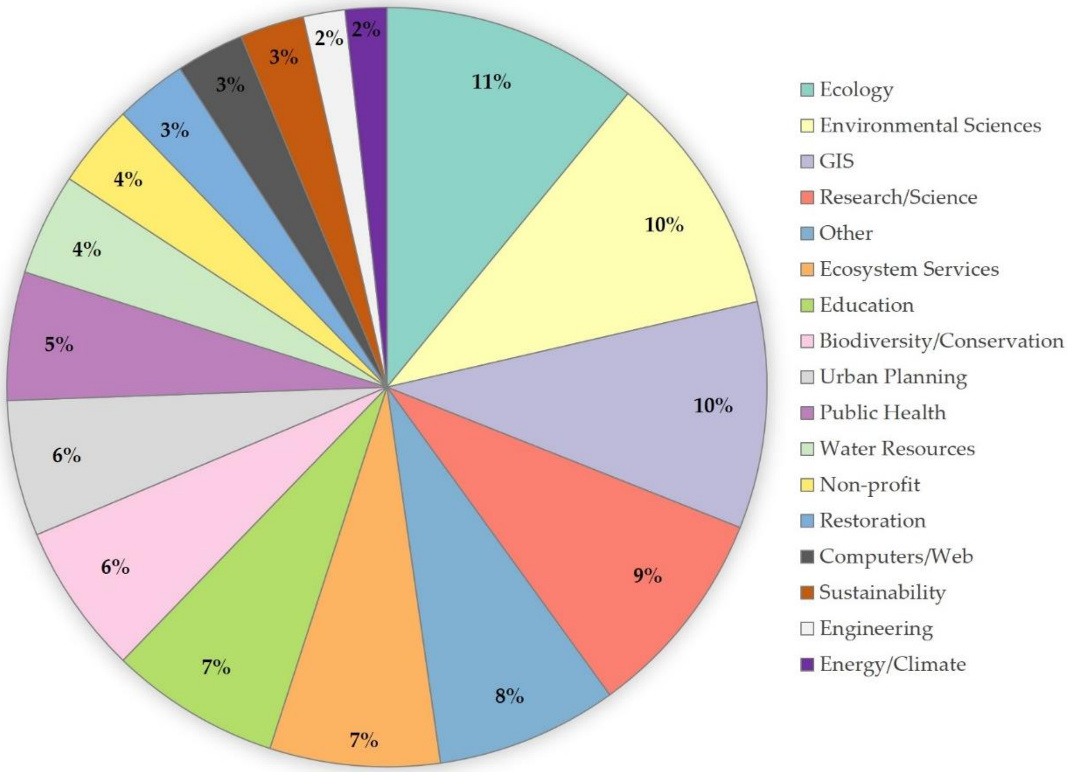

Figure 5. EnviroAtlas beta test participants by discipline (n=620).