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Geospatial data analytics for equitable forest resource management

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A B S T R A C T

Geospatial data analytics is an essential tool in the toolbox of contemporary forest engineering and natural resource management. Beyond its application in estimating wood and fiber production, geospatial data analytics also proves indispensable in conservation planning. By leveraging a myriad of geospatial datasets, forest engineers and natural resource managers make well-informed decisions regarding forest restoration and carbon sequestration that foster environmental sustainability. However, one often-underestimated aspect of geospatial data analytics is its potential to help identify and address issues of distributive justice relating to forest resources and associated benefits. Thus, this article outlines a roadmap for forest engineers and natural resource managers to harness geospatial data effectively to simultaneously promote environmental sustainability and distributive justice – that is, the fair and equitable allocation of natural resources, nature's benefits, and environmental burdens. The approach involves defining local concerns and priorities through community engagement to guide spatial data gathering, determining spatial and temporal scales of assessment, accessing and preprocessing data sources, developing prioritization indexes, performing relevant analytical tests, and creating opportunities for data return prior to decision making. Through this methodological approach, forest engineers and natural resource managers can harness the power of geospatial data to model and synthesize information, assess ecosystem services, evaluate community risks, and identify environmental hazards. In a world where data is abundant but its transformation into actionable insights is often lacking, this overview aims to illuminate the potential of geospatial data analytics as a tool that can simultaneously advance environmental sustainability and distributive justice.

Introduction

Geospatial data analytics plays a critical role in modern forest engineering and natural resource management (McGee III et al., 2012). While it is widely recognized in these fields to estimate wood and fiber production, it also aids in conservation planning (Taye et al., 2021). By leveraging geospatial data, forest engineers and natural resource managers make informed decisions regarding forest restoration and carbon sequestration. However, monitoring landscape conditions for effective management involves more than assessing biophysical properties (Gain et al., 2020).

Today, with over half of the world's population residing in urban areas, it is essential to recognize the existence of intricate socio-ecological systems that encompass both social and ecological dimensions (Gain et al., 2020). Consequently, forest engineers and natural resource managers must take into account both human and natural factors to ensure that forest resources and their associated benefits are fairly and equitably distributed, fostering distributive justice (Moroni, 2020). However, in a rapidly urbanizing world, access to nature can be limited.

Factors such as the fragmentation of natural landscapes and sociohistorical influences on policymaking, urban planning, economic development, and intentional greening and conservation (or their absence) have shaped how specific demographic groups and intersecting marginalized identities experience and benefit from nature (Schell et al., 2020). Globally, disparities in the distribution of nature and its benefits are evident. In the Global North, inequities in tree distribution based on race and income persist, often reflecting discriminatory policies of the past, such as redlining in the United States of America (Schell et al., 2020). In Global South countries, income frequently determines access to nature, and Indigenous communities may also face further disproportionate exposure to degraded environmental conditions like in the Republic of Ecuador (Rodríguez González & Torres Garrido, 2023).

Given the numerous benefits that nature provides, including cleaner air, cooler temperatures, reduced flooding, and opportunities for recreation, that positively impact human wellbeing, it is essential to promote distributive justice (MEA, 2005; Moroni, 2020). This perspective aligns with current approaches to engineering, where the term "engineering for human rights" has been coined to emphasize the significance of engineering and technology in societal development (Hertel et al., 2023). Practitioners in natural resource management have extensively documented how policy decisions have shaped the distribution of natural resources and their access to different populations and are moving to revising or expanding criteria conventionally used for land prioritization in conservation to also account for socioeconomic, health and related factors (Rodríguez González et al., 2022; Sims et al., 2022).

Geospatial secondary data analysis offers an efficient way to assess existing socio-ecological dynamics without the need for expensive and time-consuming investments (Gain et al., 2020; Singh, 2019). It is widely accepted that thorough understanding of current conditions through inventorying and monitoring is required for effectively managing forest resources – one cannot manage what is unknown (Shojanoori & Shafri, 2016). Additionally, planning and decision-making in complex socio-ecological systems requires expertise from various fields of knowledge (Gain et al., 2020). However, limited resources, personnel, and funding can hinder primary data collection efforts.

Geographic Information Systems (GIS) enable the generation, processing, visualization, and storage of diverse data types, including socioeconomic, environmental, technological, infrastructural, administrative and health data, among others (Rodríguez González & Torres Garrido, 2022). If data can be linked to a specific location on Earth's surface, it can be georeferenced. Public databases often include georeferenced information collected through sources like censuses, health surveys, and satellite imagery. The versatility and accessibility of geospatial data facilitate secondary data analysis, which involves addressing research questions using data not collected by the researcher or organization conducting the study, and ultimately integrating this data into decision-making processes (Singh, 2019; Wyborn et al., 2018). Secondary data analysis using databases from various knowledge areas (e.g., forestry, public health, socioeconomics, etc.) that can be or already is georeferenced offers an opportunity to capture key human-nature patterns and dynamics before committing to costly and time-consuming site-specific data collection.

In this article, we present a roadmap for forest engineers and natural resource managers gathering and synthesizing large volumes of geospatial data to inform forest resource management. This, combined with a formal or informal needs assessment, can provide the foundation for forestry initiatives grounded in principles of social equity (Crowley et al., 2021). The article is directed to the forestry professional managing forest resources beyond the hyper-local scale, with impacts felt at a community level or beyond.

In the following subsections, we explore the different stages of this integrated approach to managing forest resources, starting with secondary data analysis, and extending to the development of community-informed management strategies.

Step 1: Define vulnerability according to local concerns and community priorities.

Since not all communities have the same capacity to cope with or adapt to environmental challenges, the first step in this framework is defining the target community and what vulnerability is for them. Understanding the vulnerabilities of specific populations helps forest engineers and natural resource managers know what potential risks these populations face that may be addressed through environmental management (Havrilla, 2027; Sheppard et al., 2017). Vulnerabilities should be defined by asking community members directly but can be drawn from established definitions within relevant stakeholder groups as a starting point and refine it based on community input (Crowley et al., 2021; Havrilla, 2017; Sheppard et al., 2017). In this article, we adopt a broad definition for vulnerability, one that is commonly used in the health sciences but tailored for the context of forest engineering and natural resource management for community well-being: Vulnerable populations are groups and communities at a heightened risk of environmental and climate challenges due to barriers stemming from social, economic, political, and ecological factors, which are further compounded by limitations related to illness or disability (Havrilla, 2017).

While it may be tempting to immediately brainstorm the risks affecting target populations to refine this definition of vulnerability, it is crucial to engage with communities to understand their unique concerns thoroughly (Campbell-Arvai & Lindquist, 2021; Sheppard et al., 2017). This initial step is known as a needs assessment, and it can take various forms, such as primary data collection methods like surveys, interviews, and focus groups. Alternatively, it can involve an informal approach, combining a systematic review of existing literature (including journal articles, books, policy documents, newspapers, etc.) with conversations with the community (e.g., listening sessions, community forums, guided discussions, etc.) to ground themes drawn from the literature in local context.

Effective community conversations require creating spaces that encourage community members to voice their concerns regarding the issues impacting them (Rodríguez González, in revision). These spaces should be representative of the community, achieved by fostering inclusivity through provisions such as accessible locations (i.e., within the community itself, and compliant with local disability acts), the presence of community liaisons or community-trusted leaders, and the availability of time-based compensation, childcare, translators, and refreshments, as appropriate for the community (Rodríguez González, in revision).

Community conversations, whether for formal data collection or not, should count with the presence of a respectful and culturally sensitive moderator but these conversations should ultimately be shaped by the community itself (Jackon, 2019). This approach acknowledges that communities are the authorities on their own experiences and needs. Effective moderators actively listen, establish a secure and inclusive environment, and prioritize the inclusion of all voices to facilitate open dialogue (Campbell-Arvai & Lindquist, 2021). While trust-building is vital, it is essential to note that it can be a time-intensive process, ranging from days to weeks, months, or even years, depending on the existing relationship between the community and local institutions of power. Building trust not only ensures a secure space for discussions but also cultivates strategic partnerships that encourage community engagement in these conversations.

The themes that surface from needs assessments can be compared with the primary management priorities established by local agencies, which frequently emphasize the biophysical aspects of management rather than social or human aspects, to find common ground and potential starting points for a scale-appropriate assessment using primarily secondary data. Identifying these agency-based themes can be done by conducting a comprehensive review of local agency documents, reports, and planning records, and through direct communication and collaboration with these agencies. Collaboration with agencies is especially necessary if the anticipated geospatial assessment is expected to shape local policies and practices pertaining to forest resources and associated benefits (Moote, 2010).

Step 2: Determine spatial and temporal scales of assessment.

After defining local concerns and priorities, the next step is selecting the appropriate scale of assessment for the secondary data analysis.

Environmental challenges are rarely confined to a single locality. Environmental issues, such as water quality and biodiversity, transcend political borders, beyond a community and further, and may entail considering the larger context when addressing local challenges (Schröter et al., 2018). For example, effectively managing urban water runoff requires an understanding of the larger watershed within which a city resides. Watersheds encompass areas that contribute water to a common outlet, such as a river or lake. Therefore, the management of water quality and quantity in urban areas requires coordinated efforts both upstream and downstream of a city, which often means working at a watershed scale instead.

In practice, selecting the scale of assessment means integrating the local priorities and concerns identified through community engagement (i.e., Step 1 of this framework) with the broader relevant environmental context. It involves considering the interplay between local actions and their potential impacts on the surrounding areas, as well as acknowledging how regional and global phenomena can influence local conditions (Gain et al., 2020; Schell et al., 2020). Based on this understanding, it can be determined how far out and to what level of specificity an assessment must go to allow the accurate interpretation of issues that are observed locally. To understand the interplay between local management and impact in surrounding areas, a multi-scalar lens is necessary and expertise from scientific researchers and other practitioners, whether brought in as consultants or as integral members of the assessment team, can provide invaluable insights on the complex multi-scale interactions and interdependencies present (Gain et al., 2020).

A scale of assessment does not only entail a geographic range but also a time range. Environmental and community conditions, challenges, and solutions evolve over time. Factors such as climate patterns, land use, urban development, ecological processes, and evolving human dynamics, including shifting policies influenced by racism or classism, all shape the distribution of natural resources (Schell et al., 2020). Thus, understanding the historical context of a community becomes crucial for comprehending existing patterns and provides insights into addressing disparities within a realistic timeline. Ways to capture the historical context of a community include tapping into local archives, engaging with local historians and long-term residents, and analyzing historical documents, maps, photographs, newspapers, and oral recounts.

Step 3: Leverage diverse datasets to capture risk, vulnerability and mitigation.

After establishing local priorities and the scale of assessment, the next step is to identify diverse databases to use. The specific data requirements will naturally vary depending on the defined priorities, but a useful guideline is to collect data pertaining to (a) identified environmental hazards that have surfaced as concerns through the needs assessment, (b) populations that are vulnerable to these hazards, and (c) any natural features, such as vegetation cover, which could potentially help mitigate the community's exposure to these hazards.

At the community scale, databases within municipal boundaries, while occasionally lacking fine-tuning, offer access to a wide array of local datasets. These datasets encompass a broad spectrum of information, including tree inventories, drone-captured images of the local tree canopy, statistics related to hospitalizations due to heat-related stress, sewer overflow reports, and many more. Building strong collaborations with key local agencies can substantially enhance our capacity to tap into these invaluable datasets (Moote, 2010). For instance, when a forest engineer collaborates with the Department of Public Health or its local equivalent, they can gain access to data on local asthma rates, which can be utilized to assess the role of trees in purifying the air and contributing to community health.

In cases where there is little to no site-specific data, regional, national, and even global sources may be used. However, the process of finding and navigating these data sources can be overwhelming. To alleviate this challenge, Table 1 provides a list of overarching themes and example of relevant search terms that can help guide an extensive data search. It is important to acknowledge that the availability of accessible databases can significantly depend on the specific location of the assessment.

Table 1. Overarching themes and relevant search terms to guide an extensive data search at the local, regional, national or global scale in a general search engine. Example of susceptible populations and natural features for mitigation are included.

Environmental hazards (themes and search terms)	Example of susceptible populations	Example of natural features for mitigation
Heatwaves and temperature extremes *Search terms: temperature, daily maximum temperature, urban heat island, impervious surface area*	Elderly (age >65), children (age <18), low-income residents, racial and ethnic minorities, homeless individuals, individuals with preexisting health conditions (those with heart conditions, respiratory problems, or other illness), outdoor workers	Tree canopy, vegetation cover, parks, forests, urban greenery, lakes, rivers, ponds
Flooding and water related hazards *Search terms: flood risk, floodplain, water bodies, flooding, runoff, rainfall, precipitation, sewer backup, sewer overflow, impervious surface area*	Individuals living in flood-prone areas, low-income residents, racial and ethnic minorities, elderly, children disabled individuals, homeless individuals	Wetlands, riparian vegetation, floodplains
Air quality and pollution *Search terms: air pollution, particulate matter (e.g., PM2.5), ground-level ozone*	Elderly, children, individuals with respiratory conditions, low-income residents, racial and ethnic minorities, workers in polluting industries, urban residents	Tree canopy, vegetation cover, parks, forests, urban greenery, wetlands, vegetated swales, clean air corridors
Wildfire and fire risk *Search terms: wildfires, fire risk, burn sensitivity*	Individuals living in wildfire-prone areas, elderly, children, individuals with mobility issues, low-income residents, racial and ethnic minorities, outdoor workers, firefighters	Firebreaks, controlled burns, fire-resistant plants
Seismic and earthquake hazards *Search terms: seismic activity, earthquake epicenters, fault lines*	Urban residents, elderly, children, disabled individuals, low-income residents, racial and ethnic minorities, homeowners and renters (housing stability and safety measures may vary)	Open spaces, parks, underdeveloped land, trees and vegetation (can help stabilize soil and decrease landslide)
Industrial and chemical hazards *Search terms: chemical spills, hazards, industrial zones, affecting facilities*	Industrial workers, individuals living near industrial sites and affecting facilities, low-income residents, racial and ethnic minorities, emergency responders	Natural buffer zones, floodplains, phytoremediation
Hazardous waste sites *Search terms: superfund sites, hazardous waste disposal, toxic waste sites, brownfields*	Individuals living near waste sites and affecting facilities, low-income residents, racial and ethnic minorities, elderly, children, individuals living near impaired waterways, outdoor workers	Wetlands, soil microbes, geological features (e.g., clay and slit layers, bedrock, aquicludes, low-permeability soils, confining layers, kettle holes, potholes, alluvial fans, karst) that may slow the movement of contaminants

Once relevant data sources have been identified, it is important to preprocess datasets (i.e., prepare and clean the data) to ensure compatibility and readiness for analysis and integration. Organizing datasets using a file hierarchy system can streamline data management and simplify the process of exploring, comparing, or merging datasets, particularly when dealing with redundancies or gaps. Furthermore, most datasets are accompanied by metadata, which contains vital information about the data, such as its source, collection date, and other pertinent details. When working with data from various sources, it is necessary to apply inclusion and exclusion criteria (examples of such criteria are provided in Table 2) to ensure data quality and relevance while acknowledging that there may be instances where trade-offs or compromises are necessary. Metadata can assist in preliminarily evaluating some of these criteria before delving into the dataset itself.

Table 2. Inclusion and exclusion criteria for secondary data. By methodically applying these criteria, forest engineers and related professionals can establish the assurance that any data used maintains a high standard of quality and aligns with the defined priorities.

Criteria	Included	Excluded
Relevance/Irrelevance	Data must be directly related to the identified project scope.	Data does not relate to the identified project scope.
Accuracy/Inaccuracy	Ensure data is accurate, reliable and trustworthy, where any errors can be corrected.	Data has uncorrectable errors or inconsistencies.
Completeness/Incompleteness	Data should contain all necessary variables and information.	Data is missing critical information, consider exclusion.
Recency/Outdated	Use the most up-to-date data available for analysis.	More recent data is available.
Consistency/Inconsistency	Data fits units and formats being used or can be easily converted.	Data does not align with the overall dataset's format and cannot be converted, or units are excluded and cannot be identified.

Step 4: Process, analyze and integrate.

Data processing should go according to the priorities identified, but a few starting points include (a) identifying patterns in the distribution of environmental hazards and affecting facilities and examining these in relation to local communities, (b) ranking community risk to these environmental hazards to prioritize the most susceptible, and (c) quantifying or modeling the ability of existing vegetation and natural features to mitigate these hazards.

Assessing environmental hazards starts with the acquisition of satellite imagery, historical weather records, environmental datasets, pollution records, etc. To effectively monitor current patterns and predict future ones based on historical data, analysts leverage open-source tools such as QGIS and the R statistical software for advanced spatial analysis on current patterns or to predict future ones (QGIS.org, 2023; R Core Team, 2021). The outcomes of this analysis, often translated into hazard or hotspot maps, can be enriched with qualitative insights derived from community engagement. Validation with ground-truth data and interdisciplinary collaboration with domain experts further enhance accuracy and informs mitigation strategies and policy recommendations (Sharp et al., 2020).

Evaluating the capacity of both existing and future vegetation, as well as other natural features, to mitigate hazards can be done through ecosystem service modeling and mapping. Ecosystem services represent the various benefits derived from nature, including clean air, water purification, pollination, and climate regulation, among others. To perform such assessments, tools like the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) and similar applications are employed (Sharp et al., 2020). These tools combine a wide array of environmental data, geospatial technology, and advanced statistical modeling techniques to quantify the ecological benefits provided by these natural elements (Sharp et al., 2020). This process results in the creation of detailed maps that illustrate the distribution of ecosystem services across a given area. These maps, in turn, serve as valuable decision-making resources for various applications, such as natural resource management, urban planning, and conservation efforts, including the exploration of different land use scenarios.

By integrating Geographic Information Systems (GIS), demographic data, and hazard mapping, it becomes possible to create prioritization or weighted indexes that help pinpoint vulnerable areas and populations. These composite vulnerability indexes provide a comprehensive perspective, with the weighting process enhancing the precision of the index. Weights can be derived from a variety of sources, including data from existing literature, insights from practitioners and agencies, or community perspectives on the factors that hold the greatest significance or urgency (Campbell-Arvai & Lindquist, 2021; Moote, 2010; Sheppard et al., 2017). Through the overlay of vulnerability and risk maps, high-risk and high-vulnerability regions can be discerned, supporting the planning of targeted interventions like tree plantings for priority neighborhoods.

Step 5: Ground interpretations in local knowledge through data return and co-develop solutions.

In the context of environmental analysis and community engagement, "data returns" refers to the process of delivering research findings and insights to decision-makers, practitioners, stakeholders, and community members. This step is essential for translating complex data and analyses into actionable information. Reporting to decision-makers empowers them to make informed choices about policies, resource allocation, and interventions to address environmental hazards and community vulnerabilities (Moote, 2010). Engaging with practitioners ensures that those responsible for implementing strategies fully understand the data-driven recommendations (Campbell et al., 2016). However, involving community members in the data return process is equally important as it empowers them with information about local risks and vulnerabilities, helps validate that the conclusions accurately reflect their lived experiences, and enriches any conclusions with community insights that might not be evident from spatial assessments alone (Campbell-Arvai & Lindquist, 2021; Sheppard et al., 2017). Visioning sessions, design charrettes, and community workshops can serve to engage communities in the process of developing management strategies.

Establishing an action plan and relevant policies based on the findings of community engagement and spatial data analysis requires a comprehensive approach. First, the identified hazards and vulnerabilities should inform the development of specific mitigation strategies, such as flood-resistant infrastructure or heatwave preparedness programs that integrate nature-based solutions (Campbell-Arvai & Lindquist, 2021). These strategies must align with the community's vision, as obtained through visioning sessions and design charrettes. Additionally, policies should be crafted or adjusted to support these strategies, ensuring that they are legally enforceable and backed by adequate resources. Community input, through workshops and feedback mechanisms, can allow for adaptable management. Collaboration with experts, policymakers, and practitioners will help bridge the gap between community aspirations and effective policy implementation, ultimately enhancing resilience and reducing the impact of environmental hazards on vulnerable communities.

Conclusions

Geospatial data analytics is a crucial tool for modern forest engineering, allowing professionals to manage forests and natural resources effectively. It goes beyond economic estimations and encompasses conservation planning, leading to sustainable forest management. Furthermore, the integration of both social and ecological aspects is essential for equitable resource distribution in complex socio-ecological systems. By using secondary spatial data analysis, human-nature dynamics, environmental risk, community vulnerability, and local vegetation capacity for mitigation can be assessed. Collaboration with experts and community engagement are key to achieving comprehensive and actionable insights. Data returns to decision-makers, practitioners, and communities are vital for translating complex data into actionable strategies, ultimately enhancing resilience and reducing the impact of environmental hazards on vulnerable populations.

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Conflict of Interest

The authors declare no conflict of interest.

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